# Chemical Engineering Progress

# OPINION COMMENT

# TIME TO STOP FOOLING

IN the magazine, *Life* (Sept. 18, 1950), a photograph appeared of a young Marine in Korea, with tears streaming down his cheeks, crying "No more ammo." Translate the word "ammo" into the more generalized term, "munitions," and this photograph deserves the earnest consideration of everyone concerned with directing the policies on national defense, from the President of the United States down. It is understandable that the problem of supplies is one of delivery as well as procurement, and that therefore there are two parts to the question, but concentration on delivery and neglect of procurement is a fool's policy.

The argument for supplies is as important as the argument for "bodies." We dislike repeating clichés but it must be impressed over and over upon the people of the United States that our only chance of winning against the forces opposed to us lies in competition with brains rather than with bodies. If we depend entirely upon the latter, we are lost, and will become the greatest slave state in history. The most efficient use of our manpower is the greatest problem now facing these United States, and recent events have shown that it is time to stop fooling.

The general theory that every physically capable man between 26 and 19 must be in the Army is a little-boy idea, devoid of sufficient reflection and empty of judgment.

The report of the Six Advisory Committees to the Selective Service System presented to General Hershey in Washington a few weeks ago indicated a reasonable method of attaining the objectives which we seek. The fact that we are told that this state of mobilization may last for many years, even if no war breaks out, indicates the justice of the Committees' recommendations that there should be a steady flow through the universities of selected students, under conditions of proper safeguards with regard to standards and accomplishments. Industry is being asked to expand and to expand rapidly. Such expansion requires management personnel which must be drawn from older, more experienced men. Their places, in turn, must be taken by younger men, and theirs, in turn, by embryo graduates. Immediately this poses many problems for management but none of them is as bad as having no replacements which will force cessation of production. Who wants to take the responsibility, for the sake of having a few more infantrymen, that our G.I.'s have no more ammo?

Equally important is the recommendation of the Committees that these graduates be given four months to get settled in an important war industry. It is futile to train them and induct them on the day of their graduation. This is so obvious that it does not seem to be seen, and thousands of technical seniors are in this position in this country today.

We must be sure to look at both sides of this question. The Armed Forces, too, have a job to do, and it is the teamwork between them and industry which will win any war that we may have. It would seem fair, therefore, that when there is a question of the induction or calling into Service of engineers and other technically trained men the problem should be looked at from a more judicial standpoint than has been the case heretofore. At present the burden of proof is entirely on the industrial side. No mention is made of what is going to happen to the man when he gets into the Armed Forces. It would seem, therefore, proper that the Armed Forces should present their reasons for induction at the same time that industry presents its request for deferment, and that the judgment should be made on the basis of where that man can best serve his country. There are many uses for technical men in the Armed Services and they may well be more important than the work which the individual is carrying on in industry, and such cases should be properly weighed and properly adjudicated. By some such process as this, the people of the United States can be assured that their fringe of technical superiority is not being frittered away and that if the Korean G.I. has no more ammo, it is from lack of resources and not stupidity in their utilization.

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# SEPARATION OF GAS MIXTURES BY MASS DIFFUSION

## PART I

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## 1. Introduction

THE three principal methods for separating gases by diffusion are thermal diffusion, gaseous diffusion and mass diffusion. Thermal diffusion has been used extensively for small-scale separation of isotopes of the lighter elements and for large-scale partial separation of the uranium isotopes; its commercial utility has been limited, however, by its comparatively low separation factor and poor thermal efficiency. Gaseous diffusion has been used with marked success for large-scale separation of uranium isotopes; its commercial application to other separations has been limited by the large number of high compression ratio gas compressors and the large areas of special diffusion membranes with fine holes required by this operation.

Mass diffusion, on the other hand, has had few laboratory or commercial applications; nevertheless, it has a number of advantages compared with thermal diffusion or gaseous diffusion which may cause it to be the preferred operation for certain separations. It has the highest separation factor of all diffusion separation operations and is more efficient than thermal diffusion, although not so efficient as gaseous diffusion. It requires no special pumps or special diffusion membrane, and it may be operated at, or somewhat above, atmospheric pressure. Since mass diffusion is not applicable to separation of uranium isotopes, there are no restrictions on the commercial use of this process. Because of these advantages of mass diffusion, it has seemed appropriate to develop the principles of this operation in enough detail that possible laboratory or commercial applications of mass diffusion may be reliably evaluated. This is the main objective of this paper.

Two principal applications are fore-

seen for mass diffusion: (1) separation of isotopes, and (2) partial extraction of hydrogen or helium from mixtures with gases of higher molecular weight. Both applications will be treated.

Separation by mass diffusion may be carried out in a stage type of process, analogous to solvent extraction in a series of separate contacting units, or in a column, analogous to solvent extraction in a packed column. The stage type of mass diffusion was developed originally by Hertz (3),‡ who patented the process (4) and used it for separation of helium from neon, and neon-20 from neon-22 (5). More recently, Maier (6) has conducted a thorough experimental study of the use of a mass diffusion stage to separate hydrogen from nitrogen, sulfur dioxide or air, and has worked with other mixtures of industrial importance. Maier termed the operation "atmolysis."

The column type of mass diffusion has not been described previously.

## 2. Qualitative Description of Mass Diffusion

*2.1 Mass Diffusion Stage.* The means by which separation is effected in a mass diffusion stage are shown in Figure 1, which represents the type of apparatus used by Maier. In Maier's apparatus, the mass diffusion stage is of cylindrical cross section, and is divided into two annular chambers by the cylindrical mass diffusion screen. Feed gas is admitted at the top of the inner compartment. As this stream flows downward through the inner chamber, it picks up separating agent, which diffuses through the screen from the outer chamber, and gives up a portion of the feed, which diffuses through the screen into the outer chamber against the incoming separating agent. Because the light components of the feed diffuse at a higher velocity than the heavy components, the stream in the inner chamber is progressively enriched in the heavy components, and for this reason, is called the *heavy stream.*

Steam, or other separating agent vapor, is admitted at the bottom of the outer chamber. As this stream flows upward countercurrent to the descending heavy stream, it gives up separating agent to the

heavy stream and picks up from it a portion of the components of the feed, enriched with respect to the light components. For this reason, this stream is called the *light stream.*

After the light and heavy streams leave the diffusion stage, they are cooled to condense out the separating agent. After separation of the condensate, they leave the apparatus, respectively, as the heads and tails fractions of the separation.

Main controls of the apparatus are valves to adjust the rate of charging feed (not shown), the rate of charging separating agent ($V_1$) and the split of feed between heads and tails ($V_2$). As $V_2$ is opened, the pressure of the light stream is reduced relative to the heavy stream, and more of the feed enters the heads fraction. Separation takes place either when the pressure of the light stream is greater than that of the heavy stream or when the reverse is true, but the most efficient operation occurs when the light stream is at slightly higher pressure.

Many types of equipment besides that shown in Figure 1 may be used in a mass diffusion stage. For example, the directions of flow may be reversed, or horizontal rather than vertical. The apparatus may be of the multitube-and-shell type construction, like a tubular heat exchanger, or of the parallel-plate type, in which light and heavy streams alternate. Cross flow or concurrent flow may be used rather than countercurrent, although with some sacrifice of efficiency.

For the diffusion screen, Maier used a wide variety of material, such as plates perforated with 1/64-in. holes, fine mesh wire screen, and alundum filter plates. A porous membrane with fine holes, such as is needed in gaseous diffusion, is not required in mass diffusion, although holes with a diameter under ten microns are preferred because control of pressure differences across the screen is simpler than when larger holes are used. Porous metal sheet, such as is used for oil filters, makes an admirable mass diffusion screen.

The main requirements of the separating agent are that it be selective, have a high diffusion coefficient into the feed, and be readily separable from the products of the separation. Generally speaking, a separating agent with high molecular weight is more selective than one with low, but its diffusion coefficient into the feed is lower. When the components are permanent gases, such as hydrogen and nitrogen, a readily condensable vapor such as steam, is preferred as separating agent. When the components to be separated are condensable vapors, such as ethyl alcohol and water, it is

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‡ Literature references will be printed with the final installment of this article.
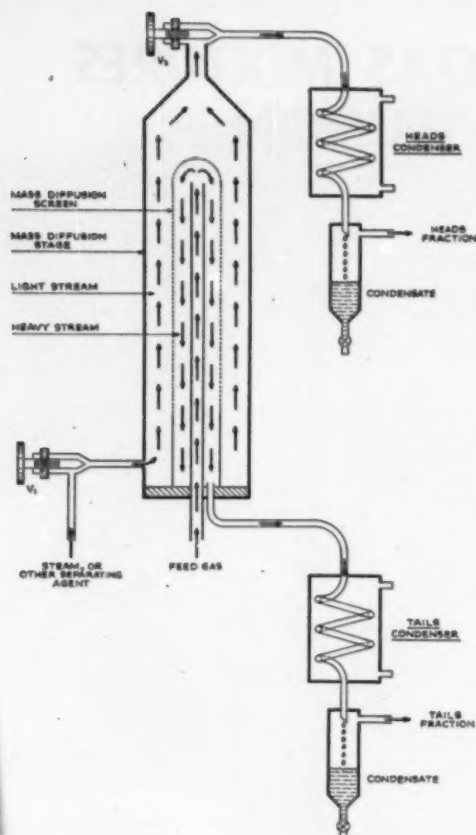
Fig. 1. Mass diffusion
stage used by Maier.

(Figure labels:)
MASS DIFFUSION SCREEN
MASS DIFFUSION STAGE
LIGHT STREAM
HEAVY STREAM
HEADS CONDENSER
HEADS FRACTION
CONDENSATE
STEAM, OR OTHER SEPARATING AGENT
FEED GAS
TAILS CONDENSER
TAILS FRACTION
CONDENSATE

convenient to use a permanent gas, such as air, as separating agent. Although mass diffusion may, in principle, be carried out in liquid mixtures, the low diffusion coefficients in liquids rule out this operation in practice.

In previous applications of mass diffusion, the process has been run at atmospheric pressure (Maier) or a few centimeters of mercury (Hertz). Operation above atmospheric pressure would be possible, but the delicate balance of pressure across the diffusion screen becomes harder to maintain, the higher the pressure.

Two examples may be given of the degree of separation attainable in mass diffusion. Suppose that a mixture of 50% $H_2$ and 50% $N_2$ is maintained at one end of the diffusion zone, and 100% steam is maintained at the other end. When the number of moles of steam diffusing in one direction equals the number of moles of hydrogen and nitrogen diffusing in the opposite direction, the composition of the diffused mixture will be 85.0% $H_2$ and 15.0% $N_2$. This is a favorable example, because the diffusion coefficients of hydrogen and nitrogen into steam are in the ratio of 3.43 to 1. When the ratio of the diffusion coefficients is lower, the degree of separation will be correspondingly reduced. In separating $C^{12}H_4$ from $C^{13}H_4$ by mass diffusion into steam, the ratio of diffusion coefficients is only 1.015, and under the conditions cited here, the gas diffused from a 50% mixture would be enriched in $C^{12}H_4$ only to 50.4%.

2.2 *Cascade of Mass Diffusion Stages.* When the degree of separation obtainable in a single stage of this type of mass diffusion is small, as with isotopes, the process must be repeated in a number of stages. Figure 2 illustrates the equipment that would be required in a cascade of mass diffusion stages, using steam as separating agent. The gaseous feed to each stage would be introduced by means of a circulating pump, and partially separated by the stage in the manner just described. After condensing the steam and separating the water from the heads and tails fractions leaving the stage, the heads fraction is sent to the next stage toward the "top" of the cascade, and the tails fraction is sent to the next stage toward the "bottom" of the cascade. To obtain both components in a relatively pure state, it is necessary to use rectifying and stripping sections in the same manner as in a distilling column.

2.3 *Mass Diffusion Column.* The mass diffusion column illustrated in Figure 3 provides a second means for obtaining a greater degree of separation than from a single stage. This apparatus makes use of the mass diffusion principle in a true countercurrent column, which, if long enough, could, in principle, effect complete separation of the components of the feed without the use of a cascade of columns.

The main differences between a mass diffusion column and a mass diffusion stage are (1) Separating agent is charged to the light stream at a uniform rate over the

entire length of the column, instead of at one end only, and (2) Separating agent is condensed from the heavy stream at a uniform rate over the entire length of the column, instead of from the heads and tails fractions leaving the stage. To permit uniform charging and condensation of separating agent, a mass diffusion column contains four compartments instead of the two used in a mass diffusion stage. These compartments may take the form of concentric cylindrical shells (Fig. 3) or parallel rectangular ducts.

The innermost chamber carries separating agent; the second chamber, the light stream; the third chamber, the heavy stream; and the fourth chamber, cooling water. Separating agent vapor enters the bottom of the perforated pipe making up the innermost chamber, and flows radially through the holes of this pipe and through the mass diffusion screen to the cooling surface between the third and fourth chambers, where it is condensed. The condensate is withdrawn with the heavy stream from the bottom of the column.

The mass diffusion screen divides the second chamber, carrying the light stream, from the third chamber, carrying the heavy stream. As the light stream flows upward through the second chamber, it is progressively enriched in the light components, which diffuse through the screen against the separating agent. As the heavy stream flows downward, it is progressively enriched in the heavy components, which are carried through the screen with the outflowing separating agent.

By proper control of light and heavy stream and separating agent feed rates, it is possible to adjust the concentration of separating agent on either side of the screen, and its flow rate through the screen, so that the molal flow of light component through the screen against the separating agent just equals the molal flow of heavy component through the screen in the other direction. This is the preferred condition for operating this type of column for the separation of isotopes. This condition, in which the flow of light component through the screen in one direction is just balanced by the flow of heavy component in the other direction, is called "balanced mass diffusion."

The use of a screen is not essential to this type of mass diffusion, since under proper conditions, convection currents may be used to set up the desired countercurrent flow. However, the performance of the column then becomes much more sensitive to the changes in gas density and static head resulting from the concentration and temperature gradients in the column, and its performance is more difficult to control.

Although experimental use of a mass diffusion column has not been reported, it would seem to offer two important advantages over the stage. The mass diffusion column is the more efficient separating device, because it is possible to maintain optimum conditions over the full extent of its screen area. This is not possible in the stage, because separating agent concentrations and velocities through the screen change from point to point. The other main advantage of the mass diffusion column is its ability to achieve a degree of separation equivalent to many stages in a single piece of equipment. The main disadvantage of the mass diffusion column is its complex, four-chamber con-

struction, which makes difficult assembly of large amounts of screen area in a single column.

## 3. Diffusion in Multicomponent Mixtures

The transport of each component of a multicomponent mixture is measured by its molal velocity, with dimensions of moles per unit area, per unit time. In the general case, the molal velocity is a vectorial quantity, dependent on the pressure gradient, the temperature gradient, the gradient in the mole fraction of each of the components of the mixture and the bulk motion of the mixture. The theory of diffusion in this case for a general two-component mixture of gases at low pressure has been treated by Chapman and Cowling (1). Their results have been extended to multicomponent mixtures by Curtiss and Hirschfelder (2). In this paper, complications introduced by pressure and temperature gradients will be neglected and an assumption made that all mole fraction gradients, $dx_i/dr$, lie in the same line. Under these conditions, the molal velocity, $N_i$, of each component will lie in the same line as the mole fraction gradients. $N_i$ will be considered positive when in the direction of increasing $r$; negative, when in the opposite direction.

Under these simplifying assumptions, molal velocities and mole fraction gradients in an $n$-component gas mixture at low pressures are interrelated by the system of equations:

$$\frac{dx_j}{dr} = \sum_{i=1}^{n} \frac{N_i x_j - N_j x_i}{\rho D_{ij}} \; ;$$
$$(j = 1, \cdots, n) \qquad (1)$$

Here, $x_i$ is the mole fraction of the $i$th component, $\rho$ is the density of the gas mixture in moles per unit volume, and $D_{ij}$ is the diffusion coefficient of the $i$th and $j$th components. An equivalent set of equations was given by Sherwood (7), who assumed, as this paper does, that $D_{ij}$ is independent of composition and has the value observed in a binary mixture of components $i$ and $j$.

Equation (1) reduces to the familiar expression for diffusion in a nonflowing binary mixture, for which $N_2 = -N_1$ and $x_2 = 1 - x_1$. With these substitutions, Equation (1) becomes:

$$\frac{dx_1}{dr} = \frac{-N_1}{\rho D_{12}} \qquad (2)$$

It will be noted that only $n - 1$ of the $n$ Equations (1) are independent, since

$$\sum_{j=1}^{n} \frac{dx_j}{dr} = 0.$$

## ABSTRACT

Separation of the components of a gas mixture by mass diffusion is effected by taking advantage of different rates of diffusion of its components into steam or other separating agent. Two types of apparatus may be used in this separation method, a mass diffusion stage or a mass diffusion column.

In the stage type, the mixture to be separated is fed on one side of a mass diffusion screen, and separating agent on the other. Those components with higher diffusion coefficient diffuse preferentially through the screen and are discharged with separating agent as the heads fraction of the separation; those components with lower diffusion coefficient remain preferentially in the undiffused or tails fraction of the separation. Separating agent is condensed from each fraction after it leaves the stage.

When the difference between diffusion coefficients is large, as when hydrogen or helium is to be separated from other components, a useful degree of separation can be obtained from a single stage. When the difference between diffusion coefficients is small, as in mixtures of isotopic substances, a cascade of many stages is needed for useful separation.

In the column type, steam or other condensable separating agent is caused to flow from one wall of the column, through the mixture being separated, to the other wall, where it is continuously condensed throughout the entire length of the column. The portion of the mixture being separated which is caused to flow along the wall at which the separating agent is charged becomes enriched in the components with higher diffusion coefficients; a second portion of the mixture, which is caused to flow in the opposite direction along the wall at which separating agent is condensed, is enriched in the components with lower diffusion coefficients. By using a column of sufficient length, any desired degree of separation may be secured.

Theoretical equations are derived for the performance of both the stage and column types of mass diffusion and are applied to the separation of isotopes and the extraction of hydrogen from coke oven gas or similar industrial gas mixtures.

Specific examples are given of the design of a cascade of columns and a cascade of stages, to produce 100 g./day of carbon-13, 90% pure by mass diffusion of methane into steam, starting with natural methane containing 1.06% $C^{13}H_4$. It is shown that the column type of process is the more efficient, using less diffusion screen and consuming less steam than the stage type.

The main features of a mass diffusion column to produce 90% pure hydrogen from coke oven gas containing 50% hydrogen in 90% yield are described. The thermodynamic efficiency of this separation is only 1.1%. Since an efficiency of around 10% can be obtained when hydrogen is separated by partial condensation at low temperatures, mass diffusion will be at a serious disadvantage in respect to operating cost. The main advantage of mass diffusion in extraction of hydrogen is in the relatively simple equipment used.

The equipment of a single mass diffusion stage is even simpler, but it does not permit the relatively complete separation of hydrogen obtainable with a mass diffusion column. However, a 50% yield of hydrogen, 90% pure, from coke oven gas is possible in a single stage. The main features of such a stage are described.

Experimental results secured by C. G. Maier (6) in separating hydrogen from nitrogen by a mass diffusion stage are found to be in fair agreement with the theory developed in this paper.

It is concluded that the principal applications of mass diffusion will be to the separation of isotopes, and possibly, to the extraction of hydrogen or helium from heavier gases at places where large amounts of low-pressure steam or other condensable vapor are available.
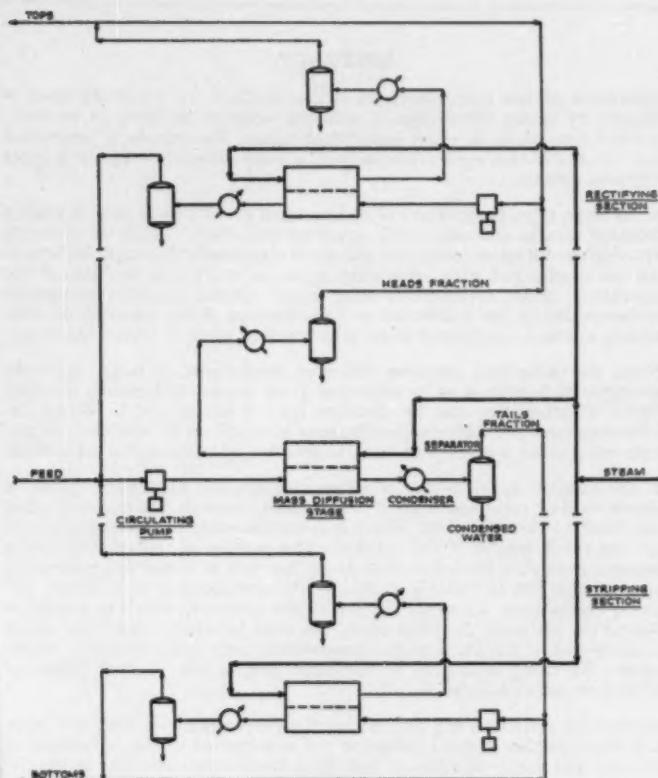
Fig. 2. Cascade of mass diffusion stages.

To evaluate all $n$ molal velocities, an auxiliary condition is required. This extra condition will be taken as

$$\sum_{i=1}^{n} N_i = N \qquad (3)$$

where $N$ is the bulk molal velocity of the entire mixture, to be assumed given.

## 4. Screen Properties

The two most important properties of a mass diffusion screen are its permeability, $C_P$, and its diffusivity, $C_D$. The permeability should be as low as practicable, to facilitate control of bulk flow through the screen, and the diffusivity should be as high as practicable, to minimize the amount of screen needed for a given separation.

The permeability is defined as the ratio of the moles flowing through the screen per unit time per unit screen area $(N)$ to the difference in pressure $(\Delta P)$ between the two faces of the screen:

$$C_P = \frac{N}{\Delta P} \quad \frac{\text{moles}}{\text{lb./sec.}} \qquad (4)$$

From Poiseuille's law for viscous flow, it may be shown that

$$C_P = \frac{\rho g d^2 \lambda}{32 \mu W_B} \qquad (5)$$

where

$g$ = acceleration of gravity
$d$ = effective mean diameter of holes in screen
$\mu$ = effective viscosity of gas (of variable composition) flowing through screen
$W_B$ = screen thickness
$\lambda$ = fraction of screen area open to flow

The diffusivity is defined as the ratio of the moles of gas diffusing into separating agent through the screen per unit time per unit screen area $(N_1)$ to the difference in mole fraction between the streams flowing past the two faces of the screen, when there is no bulk flow through the screen:

$$C_D = \frac{N_1}{x_1 - y_1} \qquad (6)$$

where $x_1$ is the mole fraction of gas in the heavy stream, and $y_1$ is its mole fraction in the light stream.

The diffusivity depends on the thickness of the screen, the fraction of its area open to flow and on the pattern of flow in the gas passages adjacent to the stream. Figure 4 illustrates how the concept of film thickness, which has been so useful in evaluating mass-transfer coefficients in distillation and absorption, may be applied to evaluation of the diffusivity in mass diffusion.

According to the film concept, resistance to diffusion is imposed not only by the holes of the screen itself, of thickness $W_B$ and $\lambda$ fraction of area open to flow, but also by stagnant films of gas adjacent to the screen on the light stream and heavy stream sides, of thickness $Z_L$ and $Z_H$, respectively.

In this paper, molal velocities will be based on the total geometric area of the screen, rather than its free area. On this basis, the molal velocity within a hole through a screen of which $\lambda$ fraction is open to flow is $N/\lambda$. In such a hole, differential Equations (1) for diffusion in a multicomponent mixture become:

$$\frac{dx_j}{dr} = \sum_{i=1}^{n} \frac{N_i x_j - N_j x_i}{\lambda \rho D_{ij}};$$
$$(j = 1, \cdots, n) \qquad (7)$$

When an effective distance, $t$, is defined as $r/\lambda$, the equations for diffusion within a hole become:

$$\frac{dx_j}{dt} = \sum_{i=1}^{n} \frac{N_i x_j - N_j x_i}{\rho D_{ij}};$$
$$(j = 1, \cdots, n) \qquad (8)$$

Within the films, outside of the screen, $t$ is the same as the actual distance $r$. The total effective distance through the films and screen, is $Z_L + W_B/\lambda + Z_H$. The integrated form of the differential diffusion Equations (8) may be used to show that the molal velocity through the combined resistances imposed by the two films and the screen is:

$$N_1 = \frac{(x_1 - y_1) D \rho}{Z_L + Z_B/\lambda + Z_H} \qquad (9)$$

where $D$ is the diffusion coefficient of component of the gases to be separated into separating agent. The denominator of this expression is called the effective diffusion length of the screen, $Z$. In terms of $Z$, the diffusivity is given by

$$C_D = \rho D/Z \qquad (10)$$

In separating components with widely different diffusion coefficients into separating agent, the diffusivity is different for each component. In isotope separation, the diffusivity is substantially independent of component.

When the flow past the screen is tur-

HORIZONTAL SECTION



VERTICAL SECTION

◀ Fig. 3. Flow in mass diffusion column.



EFFECTIVE DIFFUSION LENGTH, $Z = Z_L + \frac{W_S}{\lambda} + Z_H$

Fig. 4. Effec- ▲ tive diffusion length of screen and streams.

bulent, Sherwood (7) has shown that the film thickness may be correlated by

$$Z = 43W(Re)^{-0.83}(M\rho D/\mu)^{0.44}$$

(11)

where

$W$ = clearance of duct
$Re$ = Reynolds number, $2WG/\mu$, of gas flowing through this duct
$G$ = mass velocity of mixture flowing in this duct
$\mu$ = viscosity
$\rho$ = molal density of mixture
$M$ = molecular weight of mixture
$D$ = diffusion coefficient of gas into separating agent

Turbulent flow is preferred in the stage type of mass diffusion, but laminar flow is necessary in the column type. In laminar flow, the entire width of the channel offers resistance to diffusion, so that the simple film concept is not applicable. It may be shown that when one face of the channel consists of screen, the flow pattern in laminar flow introduces diffusional resistance equivalent to a stagnant film whose thickness is 13/35 the channel width.

These considerations show that to get maximum diffusivity from a diffusion screen, it is desirable to use a screen as thin as possible and with the maximum possible free area. The film on each side of the screen should be made as thin as possible, by using narrow ducts and turbulent flow with high Reynolds numbers, if possible. However, it is not possible to reduce the channel width or increase the Reynolds number indefinitely, because the pressure drop along the screen becomes excessive and it is then impossible to maintain the optimum pressure difference over an extended length of screen. For every screen and separation problem, a balance must be struck between film thickness and pressure drop.

To reduce the permeability and facilitate control of flow through the screen, it is advantageous to use a screen with holes of the smallest diameter consistent with uniformity of hole size and large fraction of area open to flow. The holes in the screen should be of uniform size and shape, so that separating agent will not tend to by-pass through the large holes, with back diffusion of the gases through the small ones. Porous metal sheet, 1/64 in. thick, of the type used for oil filters, with holes around ten microns in diameter, makes good mass diffusion screen.

Equations (5) and (10) may also be used to suggest preferred conditions for operating a mass diffusion screen. A high temperature is desirable because it increases the diffusivity by increasing $\rho D$, and decreases the permeability by decreasing $\rho/\mu$. A low pressure is preferable because it reduces the permeability by reducing $\rho$. With $d = 10\mu$, operation at a pressure of one atmosphere is feasible. To obtain efficient performance at higher pressures, finer holes are desirable.

## 5. Local Separation Performance of Screen for Close-Cut Mixtures

For a two-component mixture separated by diffusion into a separating agent, the system of Equations (8) is:

*Separating Agent:*

$$\frac{dx_0}{dt} = \frac{N_1 x_0 - N_0 x_1}{\rho D_{01}} + \frac{N_2 x_0 - N_0 x_2}{\rho D_{02}}$$

(12.0)

*Light Component:*

$$\frac{dx_1}{dt} = \frac{N_0 x_1 - N_1 x_0}{\rho D_{01}} + \frac{N_2 x_1 - N_1 x_2}{\rho D_{12}}$$

(12.1)

*Heavy Component:*

$$\frac{dx_2}{dt} = \frac{N_0 x_2 - N_2 x_0}{\rho D_{02}} + \frac{N_1 x_2 - N_2 x_1}{\rho D_{12}}$$

(12.2)

The desired solution of these equations will give the dependence of the molal velocities $N_0$, $N_1$, and $N_2$ on the composition of the gases flowing by a point of the screen and the molal velocity of bulk gas flow through the screen at that point.

The general solution of Equations (12) will not be treated. Solutions will be given for two special types of mixture. This section treats a close-cut mixture, such as a mixture of isotopes, in which the difference between the diffusion coefficients of the components to be separated into the separating agent is a small fraction of the diffusion coefficients themselves.

MOLAL VELOCITY
  SEPARATING AGENT        $N_0$
  LIGHT COMPONENT         $N_1$
  HEAVY COMPONENT         $N_2$
  TOTAL                   $N$

MOL FRACTIONS
  SEPARATING AGENT                        $1-\eta$
  MAIN COMPONENTS                         $\eta$
  LIGHT COMPONENT,
    SEPARATING AGENT-FREE BASIS           $\psi$
  HEAVY COMPONENT,
    SEPARATING AGENT-FREE BASIS           $1-\psi$
EFFECTIVE DISTANCE                        $0$

Fig. 5. Nomenclature for
screen performance.
Closecut case.

Section 8 treats the case in which the diffusion coefficient of light component into separating agent equals the diffusion coefficient of light component into heavy component, which is approximately true of the separation of hydrogen from nitrogen by diffusion into steam.

Figure 5 illustrates the nomenclature to be used in deriving equations for the performance of a single hole of a mass diffusion screen in separating a two-component, close-cut mixture. At any point of mass diffusion screen, the following five boundary conditions are assumed:

1. $y$, mole fraction of light component on upstream side of screen (on a separating agent-free basis)
2. $x$, corresponding mole fraction on downstream side
3. $\eta$, combined mole fraction of main components (the components being separated) on upstream side of the screen
4. $\xi$, mole fraction of main components on downstream side of screen
5. $N$, molal mass velocity of all components through screen. $N$ is determined by the pressure difference across screen, and its permeability.

The solution of this system of equations for the special case of a close-cut mixture is facilitated by taking advantage of the following properties of this case:

1. The mole fraction of light component, on a separating agent-free basis, changes only slightly between its value, $y$, in the light stream and $x$, in the heavy stream. That is:

$$\frac{y-x}{x} \ll 1 \qquad (13)$$

2. The difference between the diffusion coefficients of light and heavy components into separating agent is much less than their average. That is:

$$\gamma = \frac{D_{01} - D_{02}}{D_o} \ll 1 \qquad (14)$$

where

$$D_o = (D_{01} + D_{02})/2 \qquad (15)$$

$\gamma$, the ratio of the difference between the diffusion coefficients to their mean, is a measure of the ease of separation of the light and heavy components, and will be known as the *separability*. In the case of a mixture of isotopes,

$$\gamma = \frac{M_1 - M_2}{M_1 + M_2}\frac{M_0}{M_0 + (M_1 + M_2)/2} \qquad (16)$$

where $M$ is the molecular weight and subscripts 0, 1 and 2 refer, respectively, to separating agent, light component and heavy component.

3. The molal velocities of light and heavy components, $N_1$ and $N_2$, are nearly proportional to their mole fractions on a separating agent-free basis. It is convenient to introduce the small quantity $\delta$, defined by:

$$\delta = \frac{N_1(1-v) - N_2 v}{N_0} \qquad (17)$$

whose absolute value $\ll 1$.

The first step in solving the differential Equations (12) for the special case of a close-cut mixture is to replace the mole fractions $x_0$, $x_1$, and $x_2$ by the mole fraction of main components $\phi$ and the mole fraction of light component on a separating agent-free basis, $v$, to replace diffusion coefficients $D_{01}$ and $D_{02}$ by their average $D_o$ and relative difference $\gamma$, and to replace the molal velocities $N_1$ and $N_2$ by $\delta$ and $N$, where $N = N_0 + N_1 + N_2$. The required substitutions are:

$$x_0 = 1 - \phi \qquad (18)$$

$$x_1 = \phi v \qquad (19)$$

$$x_2 = \phi(1 - v) \qquad (20)$$

$$D_{01} = D_o\left(1 + \frac{\gamma}{2}\right) \qquad (21)$$

$$D_{02} = D_o\left(1 - \frac{\gamma}{2}\right) \qquad (22)$$

$$N_1 = (N - N_0)v + N_0\delta \qquad (23)$$

$$N_2 = (N - N_0)(1 - v) - N_0\delta \qquad (24)$$

With these substitutions, the differential Equation (12.0) becomes:

$$-\rho D_o \frac{d\phi}{dt} = [N(1-\phi) - N_0]\left[\frac{v}{1+\frac{\gamma}{2}} + \frac{1-v}{1-\frac{\gamma}{2}}\right]$$
$$+ N_0\delta(1-\phi)\left[\frac{1}{1+\frac{\gamma}{2}} - \frac{1}{1-\frac{\gamma}{2}}\right] \qquad (25)$$

and the differential Equation (12.1) becomes:

$$\rho D_o \phi \frac{dv}{dt} = -N_0\delta\left[\phi\frac{D_o}{D_{12}} + \frac{1-\phi}{1+\frac{\gamma}{2}} - (1-\phi)v\left(\frac{1}{1+\frac{\gamma}{2}} - \frac{1}{1-\frac{\gamma}{2}}\right)\right]$$
$$- v(1-v)[N(1-\phi) - N_0]\left[\frac{1}{1+\frac{\gamma}{2}} - \frac{1}{1-\frac{\gamma}{2}}\right] \qquad (26)$$

Equation (25) is put into form facilitating solution by expanding into a power series in $\gamma$ and neglecting terms of order $\gamma$ and higher powers:

$$-\rho D_o \frac{d\phi}{dt} = N(1-\phi) - N_0 \qquad (27)$$

The solution of this equation subject to the boundary conditions

$$\phi = \eta \text{ at } t = 0$$
$$\phi = \xi \text{ at } t = Z$$

is:

$$N_0 = N\frac{(1-\eta) - (1-\xi)e^{-U}}{1-e^{-U}} \qquad (28)$$

where

$$U = NZ/D_o\rho \qquad (29)$$

The reduced velocity, $U$, is a measure of the effective flow rate through the screen and films.

To facilitate solution of Equation (26), it is expanded into a power series in $\gamma$, terms in $\gamma\delta$, $\gamma^2$ and higher powers are neglected, and the equation remaining is divided by (27) to eliminate $t$. The resulting equation is:

$$\frac{dv}{d\phi} + \left[\left(\frac{N_0}{N}-1\right)v + \frac{N_1}{N}\right]\left[\frac{D_o/D_{12}}{1-\phi-N_0/N} + \frac{1-\phi}{\phi(1-\phi-N_0/N)}\right]$$
$$= \frac{\gamma v(1-v)}{\phi} \tag{30}$$

This equation may be integrated if $v(1-v)$ is treated as constant and equal to $x(1-x)$. Its solution, subject to the boundary conditions shown in Figure 5, is:

$$\frac{N_1}{N} = \left(1-\frac{N_0}{N}\right)x + \frac{(y-x)\eta(1-N_0/N)}{\eta - \left(\frac{1-\eta-N_0/N}{1-\xi-N_0/N}\right)^\mu \xi}$$

$$+ \frac{\gamma x(1-x)(1-N_0/N)}{\mu-1} \frac{1-\eta-N_0/N - \left(\frac{1-\eta-N_0/N}{1-\xi-N_0/N}\right)^\mu (1-\xi-N_0/N)}{\eta - \left(\frac{1-\eta-N_0/N}{1-\xi-N_0/N}\right)^\mu \xi} \tag{31}$$

where
$$\mu = (1-N_0/N)D_o/D_{12} + N_0/N \tag{32}$$

This equation may be simplified somewhat by replacing $N_0/N$ by its value from (28):

$$\frac{N_1}{N} = \frac{(\eta y - \xi x e^{-\mu U})(\eta - \xi e^{-U}) - \frac{\gamma x(1-x)(\xi-\eta)(e^{-U}-e^{-\mu U})}{D_o/D_{12}-1}}{(\eta - \xi e^{-\mu U})(1-e^{-U})} \tag{33.1}$$

Since $N_2 = N - N_0 - N_1$;

$$\frac{N_2}{N} = \frac{[\eta(1-y)-\xi(1-x)e^{-\mu U}](\eta-\xi e^{-U}) + \frac{\gamma x(1-x)(\xi-\eta)(e^{-U}-e^{-\mu U})}{D_o/D_{12}-1}}{(\eta - \xi e^{-\mu U})(1-e^{-U})} \tag{33.2}$$

In these equations,

$$\mu = 1 + \left(\frac{D_o}{D_{12}}-1\right)\left(\frac{\eta - \xi e^{-U}}{1-e^{-U}}\right) \tag{34}$$

These equations, together with (25), are the desired relations between the molal velocities and the composition of the gas on the two faces of the screen. They are so complex that the important features of the process are somewhat obscured. To bring out these features, two limiting cases of the solution will be treated. These are:

1. Balanced diffusion, in which $N_1 = -N_2$,
2. Equal diffusion coefficients, in which $D_{12} = D_o$.

*1. Balanced Diffusion.* In balanced diffusion, there is no net transport of the mixture being separated from one side of the screen to the other, since the molal velocity of heavy component from the upstream to the downstream side of the screen is equal to the molal velocity of light component from the downstream side to the upstream. Balanced diffusion is the preferred condition prevailing in the column type of mass diffusion.

In balanced diffusion:

$$N_0/N = 1 \qquad \mu = 1$$
$$\text{and} \qquad U = \ln \xi/\eta$$

In this case, Equation (33.1) reduces to:

$$N_1 = \frac{D_o\rho}{Z}[(y-x) - \gamma x(1-x)\ln \xi/\eta] \frac{\ln \xi/\eta}{\frac{1}{\eta}-\frac{1}{\xi}+\left(\frac{D_o}{D_{12}}-1\right)\ln \xi/\eta} \tag{35}$$

$N_0$ is the negative of this expression.

An even simpler equation is obtained when the diffusion coefficients $D_o$ and $D_{12}$ are equal:

$$N_1 = \frac{D_o\rho}{Z}[(y-x) - \gamma x(1-x)\ln \xi/\eta] \frac{\ln \xi/\eta}{\left[\frac{1}{\eta}-\frac{1}{\xi}\right]} \tag{36}$$

These equations show that, with balanced diffusion, the molal velocity of light component is made up of two elements. The first of these, proportional to the difference in light component composition $(y-x)$ between the upstream and downstream sides of the screen, tends to reduce this composition difference, or to "unseparate" the mixture. This may be thought of as a composition equalizing velocity. The second element of the molal velocity, proportional to the separability $(\gamma)$, is in the opposite direction, and tends to transport light component against the composition gradient. This may be thought of as a separating velocity. The possibility of effecting separation by mass diffusion depends, of course, on the existence of this separating velocity.

*2. Equal Diffusion Coefficients.* In this case, the mutual diffusion coefficient, $D_{12}$, of the light and heavy components, equals the average diffusion coefficent, $D_o$, of these components into the separating agent. In this case, as in case 1, $\mu = 1$, and the last term of Equation (33.1) becomes indeterminate. The limiting expression for $N_1$ in this case becomes:

$$N_1 = \frac{D_o\rho U}{Z}\left[\frac{\eta y - \xi x e^{-U}}{1-e^{-U}} - \frac{\gamma x(1-x)(\xi-\eta)e^{-U}U}{(1-e^{-U})^2}\right] \tag{37}$$

For the case of balanced diffusion, in which $U = \ln \xi/\eta$, Equation (37) reduces to (36).

## 6. Separation of Isotopes by Mass Diffusion Column

Equations just shown have given the molal velocity of the light and heavy components and separating agent as functions of:

- $y$, mole fraction of light component in light stream (on a separating agent-free basis)
- $x$, mole fraction of light component in heavy stream on same basis
- $\eta$, mole fraction of light plus heavy component in light stream
- $\xi$, mole fraction of light plus heavy component in heavy stream, and
- $U$, reduced molal velocity of all components through screen

These equations will be used to derive the theory of the performance of a column for the separation of isotopes by mass diffusion.

*6.1 Separative Work.* Mass diffusion screen performs useful separative work by transporting light component from the heavy stream to the light stream, where its mole fraction is higher, and by transporting heavy component from the light stream to the heavier. The rate at which separative work is performed on light component, per unit screen area, is $-RT_0 N_1 \ln y/x$. The corresponding expression for heavy component is $-RT_o N_2 \ln(1-y)/(1-x)$.
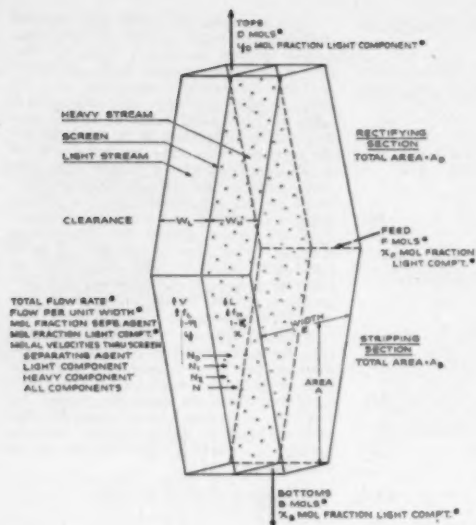
Fig. 6. Schematic flow through mass diffusion column. Quantities expressed on separating agent-free basis are denoted by (*)

The total rate of performing separative work per unit area, $W/A$ is the sum of these expressions, or

$$W/A = -RT_o[N_1 \ln y/x + N_2 \ln (1-y)/(1-x)]$$

(38)

The problem is to determine the value of $y$ which makes this expression a maximum for given values of $x$, $\eta$, $\xi$, and $U$. To take advantage of the fact that $y$ and $x$ are nearly equal in the isotope separation case, it is convenient to let

$$\frac{y-x}{x(1-x)} = \epsilon$$

(39)

where $\epsilon <\!< 1$. Equation (38) may be expanded in ascending powers of $\epsilon$:

$$\frac{W}{ART_o} = \epsilon[N_2 x - N_1(1-x)]$$
$$+ \frac{\epsilon^2}{2}[N_2 x^2 + N_1(1-x)^2] + \cdots$$

(40)

Equations (33.1) and (33.2) may be put into the form:

$$\frac{N_1}{N} = ay - bx - c\gamma x(1-x)$$
$$= (a-b)x + (a\epsilon - c\gamma)x(1-x)$$

(41.1)

$$\frac{N_2}{N} = a(1-y) - b(1-x)$$
$$+ c\gamma x(1-x) = (a-b)(1-x)$$
$$-(a\epsilon - c\gamma)x(1-x)$$

(41.2)

where

$$a = \frac{\eta(\eta - \xi e^{-U})}{(\eta - \xi e^{-\mu U})(1 - e^{-U})}$$

(42.1)

$$b = \frac{\xi e^{-\mu U}(\eta - \xi e^{-U})}{(\eta - \xi e^{-\mu U})(1 - e^{-U})}$$

(42.2)

and

$$c = \frac{(\xi - \eta)(e^{-U} - e^{-\mu U})}{\left(\frac{D_o}{D_{12}} - 1\right)(\eta - \xi e^{-\mu U})(1 - e^{-U})}$$

(42.3)

When (41.1) and (41.2) are substituted into (40), and terms of higher order than $\epsilon^2$ and $\epsilon\gamma$ are dropped, there results:

$$\frac{W}{ART_o} = N\frac{x(1-x)}{2}[2c\gamma\epsilon - (a+b)\epsilon^2]$$

(43)

This equation tells us that the separative work is positive for only a limited range of values of $\epsilon$, between 0 and $2c\gamma/(a+b)$, and that it is a maximum at

$$\epsilon_{opt.} = \frac{y_{opt.} - x}{x(1-x)} = c\gamma/(a+b)$$

(44)

At this optimum value of $\epsilon$,

$$\frac{W}{ART_o} = N\frac{x(1-x)c^2\gamma^2}{2(a+b)}$$

(44a)

$$\frac{N_1}{N} = (a-b)x - \frac{\gamma x(1-x)bc}{a+b}$$

(45.1)

$$\frac{N_2}{N} = (a-b)(1-x) + \frac{\gamma x(1-x)bc}{a+b}$$

(45.2)

6.2. Over-all Column Performance. It will next be shown how the optimum difference between the composition of light and heavy streams, expressed by Equation (44), may be realized in practice. To do this, the flow of material in a complete mass diffusion column is considered. Such a column is represented schematically by Figure 6. The column

consists of a rectifying section, which increases the light component mole fraction from $x_F$ in the feed to $y_D$ in the tops, and a stripping section which reduces its mole fraction from $x_F$ to $x_B$ in the bottoms.

For efficient operation, the downflow rate of the heavy stream, $L$, and the upflow rate of the light stream, $V$, are greatest at the feed point, and decrease toward the top and bottom of the column. To bring this out, the column has been shown as having greatest width at the feed point and least width at the product ends. In a practical case, the increased flow at the feed point would probably be obtained by using a large number of columns in parallel at this point, and a decreasing number in parallel as the product ends of the plant are approached.

To simplify the figure, the flow of separating agent into the light stream through the left face and the condensation of separating agent from the heavy stream through the right face have not been shown.

Conditions at a point in the stripping section where the mole fraction of light component in the heavy stream is $x$ are represented in the figure. It is assumed that the column as a whole is so operated that the variables shown in Table A are constant throughout its length:

TABLE A

|  | Light Stream | Heavy Stream |
|---|---|---|
| Flow per unit width ...... | $f_L$ | $f_H$ |
| Mole fraction separating agent ................ | $1-\eta$ | $1-\xi$ |
| Total molal velocity through screen ........ | | $N$ |

In isotope separation, $f_L$ and $f_H$ are substantially equal and will be denoted by $f$.

By material balance on light component, it is seen that

$$Lx = Vy + Bx_B$$

(46)

or

$$\frac{y-x}{x(1-x)} = \epsilon = \frac{B(x-x_B)}{(L-B)x(1-x)}$$

(47)

Thus, the difference in composition between light and heavy streams may be brought to its optimum value by adjusting the downflow rate $L$, to

$$L_{opt.} = B\left[1 + \frac{x - x_B}{x(1-x)\epsilon_{opt.}}\right]$$

(48)

where $\epsilon_{opt.}$, given by (44), is independent of $x$.

It is next to be established that maintenance of this optimum value of $L$ requires operation with balanced diffusion, at which $N_1 = -N_2$. A differential material balance on light plus heavy components in the heavy stream may be expressed as:

$$\frac{dL}{dA} = -(N_1 + N_2)$$

(49)

Similarly, a differential material balance on light component in the heavy stream may be expressed as:

$$\frac{dLx}{dA} = -N_1 \qquad (50)$$

By combining these equations,

$$\frac{dx}{dA} =$$

$$\frac{(N_1+N_2)x - N_1}{L} = \frac{N\gamma x(1-x)bc}{L(a+b)} \qquad (51)$$

by using (45).

Since $\frac{dL}{dA} = \frac{dx}{dA}\frac{dL}{dx}$, and $\frac{dL}{dx}$ may be obtained by differentiating (48), it is seen that $N_1 + N_2$ is given by:

$$N_1 + N_2 =$$

$$-\frac{\gamma N(x^2 + x_B - 2xx_B)}{x(1-x)\epsilon_{opt.} + x - x_B}\frac{bc}{a+b} \qquad (52)$$

Thus, $N_1 = -N_2$, except for terms of the order of $\gamma$.

From (28) it is seen that $N_1 = -N_2$ when $U = ln\,\xi/\eta$. When this substitution is made in the set of Equations (42), we obtain

*Balanced Diffusion*

$$a = b = \frac{1}{\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right) ln\,\xi/\eta} \qquad (53.1)$$

$$c = \frac{ln\,\xi/\eta}{\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right) ln\,\xi/\eta} \qquad (53.2)$$

Next, an expression for the total screen area in the stripping section will be derived from (51). By substituting for $L$ its value from (48), for $\epsilon_{opt}$ its value from (44), and for $N$ the value $\frac{D\rho}{Z} ln\,\xi/\eta$,

$$\frac{dA}{dx} = B\left[1 + \frac{x - x_B}{x(1-x)}\frac{(a+b)}{\gamma c}\right]\frac{(a+b)Z}{\gamma bcx(1-x)D_o\rho\,ln\,\xi/\eta} \qquad (54)$$

is obtained.

The total screen area in the stripping section, $A_B$, is obtained by integrating this equation from the bottoms mole fraction, $x_B$, to the feed mole fraction, $x_F$:

$$A_B =$$

$$\frac{BZ}{D_o\rho\,ln\frac{\xi}{\eta}}\left\{\frac{a+b}{\gamma bc} ln\frac{x_F(1-x_B)}{x_B(1-x_F)}\right.$$

$$+ \frac{(a+b)^2}{\gamma^2 bc^2}\left[\frac{(1-2x_F)(x_B - x_F)}{x_F(1-x_F)}\right.$$

$$\left.+ (1-2x_B)ln\frac{x_F(1-x_B)}{x_B(1-x_F)}\right]\right\} \qquad (55)$$

The term in $1/\gamma$ may be neglected relative to the term in $1/\gamma^2$, and $a$, $b$ and $c$ may be replaced by their values from (53):

$$A_B = \frac{4BZ}{\gamma^2 D_o\rho}\frac{\left[\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right)ln\,\xi/\eta\right]}{ln^2\xi/\eta}\,\pi(x_F, x_B) \qquad (56)$$

where

$$\pi(x_F, x_B) = \int_{x_B}^{x_F}\frac{x - x_B}{x^2(1-x)^2}dx$$

$$= \frac{(1-2x_F)(x_B - x_F)}{x_F(1-x_F)} + (1-2x_B)\,ln\frac{x_F(1-x_B)}{x_B(1-x_F)} \qquad (57)$$

The function $\pi(x_F,\,x_B)$ frequently appears in the theory of isotope separation, and is known as the separation potential.

The total area for the rectifying section, producing $D$ moles of tops at $y_D$ mole fraction, may be obtained by a similar treatment, so that the combined area for both sections, $A$, is given by:

$$A = \left\{\frac{4}{\gamma^2 D_o\rho}\right\}\left\{\frac{\left[\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right)\right]ln\,\xi/\eta}{ln^2\xi/\eta}\right\}\left\{B\pi(x_F, x_B) + D\pi(x_F, y_D)\right\}\{Z\} \qquad (58)$$

Here $\pi(x_F, y_D)$ is the separation potential for the rectifying section, given by

$$\pi(x_F, y_D) = \int_{y_D}^{x_F}\frac{x - y_D}{x^2(1-x)^2}dx$$

$$= \frac{(1-2x_F)(y_D - x_F)}{x_F(1-x_F)} + (1-2y_D)\,ln\frac{x_F(1-y_D)}{y_D(1-x_F)} \qquad (59)$$

Since the separating agent consumption per unit screen area is

$$N_o = \frac{D_o\rho\,ln\,\xi/\eta}{Z}$$

the total separating agent consumption in the complete column, $J = N_oA$, is:

$$J = \left\{\frac{4}{\gamma^2}\right\}\left\{\frac{\left[\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right)ln\,\xi/\eta\right]}{ln^2\xi/\eta}\right\}\left\{B\pi(x_F, x_B) + D\pi(x_F, y_D)\right\} \qquad (60)$$

Since the free energy dissipated in flow of one mole of separating agent through the screen into the heavy stream, where its mole fraction is $1 - \xi$, is $-RT_o\,ln(1-\xi)$, the minimum total work expended in carrying out this separation, $W$, is

$$W =$$

$$\left\{\frac{4RT_o}{\gamma^2}\right\}\left\{\frac{-\left[\frac{1}{\eta} - \frac{1}{\xi} + \left(\frac{D_o}{D_{12}} - 1\right)ln\xi/\eta\right]ln(1-\xi)}{ln^2\,\xi/\eta}\right\}\left\{B\pi(x_F, x_B) + D\pi(x_F, y_D)\right\} \qquad (61)$$

It is to be noted that Equations (59), (60) and (61) give the minimum values of screen area, separating agent consumption and work required for the specified separation when optimum values of the downflow rate are used at each point in the column.

6.3 Selection of Separating Agent and Optimum Operating Conditions.

To illustrate use of Equations (58), (60) and (61) in selecting a separating agent and choosing operating conditions (values of $\xi$ and $\eta$), a specific separation will be taken. Production is considered of 100 g./day of carbon-13, 90% pure, in 10% yield, by mass diffusion of natural methane, which contains 1.06% of $C^{13}H_4$: The flow rates and compositions of bottoms product, tops waste, and feed are given in Table B:

TABLE B

| | Mole Fraction $C^{13}H_4$ | Flow Rate, lb.mole/sec. |
|---|---|---|
| Bottoms | $1 - x_B = 0.90$ | $B = 2.18 \times 10^{-7}$ |
| Feed | $1 - x_F = 0.0106$ | $F = 1.95 \times 10^{-4}$ |
| Tops | $1 - y_D = 0.00955$ | $D = 1.848 \times 10^{-4}$ |

The separation potentials for stripping and rectifying sections are

Stripping,

$$\pi(x_F, x_B) = 88.3$$

Rectifying,

$$\pi(x_F, y_D) = 0.0054$$

The third factor in curly brackets in Equations (58), (60) and (61) is:

$$B\pi(x_F, x_B) + D\pi(x_F, y_D)$$
$$= 2.028 \times 10^{-5} \text{ lb.mole/sec.}$$

This is a measure of the magnitude of the job of separation.

$Z$, the effective diffusion length of the screen and ducts, will be taken as 0.111 ft.

It will be assumed that separating agent is supplied as saturated vapor at atmospheric pressure and that the screen is at the separating agent's normal boiling temperature. Steam and carbon tetrachloride will be considered as alternative separating agents. Table 1 lists the operating temperature for each separating agent, the coefficient of self-diffusion, $D_{12}$, for methane and the diffusion coefficient of methane into separating agent at this temperature, and the separability, $\gamma$, of $C^{13}H_4$ and $C^{12}H_4$ for each separating agent.

TABLE 1.—PROPERTIES OF MIXTURES OF METHANE AND SEPARATING AGENTS

| Separating Agent | Steam | Carbon Tetrachloride |
|---|---|---|
| Normal boiling point, ° F. | 212 | 170 |
| Molecular weight ........ | 18 | 153.8 |
| $10^5 \rho D_0$, lb.mole/(ft.)(sec.) | 7.0 | 2.9 |
| $10^5 \rho D_{12}$, lb.mole/(ft.)(sec.) | 7.0 | 6.7 |
| $D_0/D_{12}$ ................ | 1.00 | 0.42 |
| Separability, $\gamma$ ........ | 0.0158 | 0.0274 |

This table shows that a separating agent with molecular weight above that of the substances to be separated has an advantage because of its higher separability, but has a disadvantage because of its lower diffusion coefficient.

For each separating agent, a pair of values of $\xi$ and $\eta$ may be selected which minimizes either screen area, separating agent consumption, or work of separation; it is impossible to minimize more than one of these at a time. This point is brought out by Table 2 which for each separating agent lists pairs of values $\xi$ and $\eta$ which minimize each of these properties in turn; this table also gives the screen area, separating agent consumption and work of separation for each pair of values of $\xi$ and $\eta$.

The condition $\xi = 1$, which is needed for minimum screen area and minimum separating agent consumption results in an infinite expenditure of work because of the need for very low temperatures to condense separating agent at this mole fraction. On the other hand, the condition $\xi = 0$, which is necessary for minimum separative work, leads to infinite screen area and infinite separating agent consumption, because of the excessively dilute mixtures treated on each side of the screen. In practice, a value of $\xi$ corresponding to the lowest temperature attainable with available cooling water will be preferable. This leads to a value around $\xi = 0.9$ for steam or $\xi = 0.7$ for CCl$_4$. The practical optimum value of $\eta$ given in the table represents a compromise between those which would result in minimum screen area or minimum separating agent consumption at the practical optimum value of $\xi$.

At the practical optimum values of $\xi$ and $\eta$, the screen area needed with CCl$_4$ is somewhat higher than with steam, the higher separability with CCl$_4$ not quite offsetting its lower diffusion coefficient and lower boiling point. The weight rate of consumption of separating agent with CCl$_4$ is greater than steam because the higher molecular weight of CCl$_4$ more than offsets its higher separability. The work of separation with CCl$_4$ is much lower than with steam because of the higher separability of the former. Nevertheless, in most practical cases steam would probably be used as separating agent because of its low cost. On the other hand, in a large installation, in which fuel costs were important, the more efficient CCl$_4$ might be preferred despite its high cost.

6.4 Column Dimensions. Selection of suitable clearances for the passages carrying the light and heavy streams ($W_L$ and $W_H$, Fig. 6) and an efficient flow rate, $f$, for these streams, expressed as

moles per second per foot of column width, involves consideration of (1) pressure drops in the light and heavy streams, and (2) longitudinal back diffusion in these streams. The latter, if not controlled, will partially cancel the separation effected by the column. These factors will be taken up in turn, and used to derive two relationships between permissible values of the clearances and flow rate.

The light and heavy streams each set up a static pressure gradient depending on the gas density, and a friction pressure gradient, depending on the clearance and flow rate. It is desirable to choose such flow rates and clearances that the net pressure gradients in both streams are equal, thus maintaining a constant pressure difference across the screen.

The pressure gradient, in pounds per cubic foot, in the heavy stream, flowing down, is:

$$-\frac{dP_H}{dH} = M_H \rho_H - \frac{12 f \mu_H}{g \xi \rho_H W_H^3} \tag{62}$$

the first term being the static pressure gradient, and the second the friction pressure gradient, given by Poiseuille's law. Similarly, the pressure gradient in the light stream, flowing up, is:

$$-\frac{dP_L}{dH} = M_L \rho_L + \frac{12 f \mu_L}{g \eta \rho_L W_L^3} \tag{63}$$

If these gradients are to be equal, we must have:

$$f = \frac{g[M_H \rho_H - M_L \rho_L]}{12 \left[ \dfrac{\mu_H}{\xi \rho_H w_H^3} + \dfrac{\mu_L}{\eta \rho_L W_L^3} \right]} \tag{64}$$

The longitudinal gradient in mole fraction of light component $dx/dH$, gives rise to longitudinal back diffusion of light component at the rate of $f_L'$ moles per second per foot of screen width in the light stream, and equal but opposite longitudinal back diffusion of heavy component. $f_L'$ is given by

$$f_L' = -W_L \eta D_o \rho \, dx/dH \tag{65}$$

TABLE 2.—TOTAL SCREEN AREA, SEPARATING AGENT CONSUMPTION AND WORK OF SEPARATION AT OPTIMUM OPERATING CONDITIONS

Production of 100 g. C$^{13}$/day, 90% Pure, from Natural Methane

| Separating Agent | Condition | Mole Fraction Methane | | Screen Area, sq.ft. ($A$) | Separating Agent Consumption, lb./sec. ($JM_e$) | Work of Separation, KW ($W$) |
|---|---|---|---|---|---|---|
| | | Heavy Stream ($\xi$) | Light Stream ($\eta$) | | | |
| Steam | Min. screen area | 1.0 | 0.067 | 36,700 | 11.16 | ∞ |
| | Min. sep. agent | 1.0 | 0.25 | 55,266 | 9.89 | ∞ |
| | Minimum work | 0.0 | 0.0 | ∞ | ∞ | 529 |
| | Practical optimum | 0.9 | 0.1 | 43,030 | 10.74 | 1468 |
| CCl$_4$ | Min. screen area | 1.0 | 0.097 | 26,600 | 25.2 | ∞ |
| | Min. sep. agent | 1.0 | 0.322 | 42,666 | 16.7 | ∞ |
| | Minimum work | 0.0 | 0.0 | ∞ | ∞ | 189 |
| | Practical optimum | 0.7 | 0.15 | 30,900 | 20.4 | 246 |

The loss in separative work due to this diffusive flow of light component, per unit screen area, is given by:

$$-RT_o f_L' \frac{d \ln x}{dH} = \frac{RT_o W_L \eta D_o \rho}{x}\left(\frac{dx}{dH}\right)^2$$

(66)

Similarly, the loss in separative work due to diffusive flow of heavy component is:

$$-RT_o(-f_L') \frac{d \ln(1-x)}{dH}$$
$$= \frac{RT_o W_L \eta D_o \rho}{(1-x)}\left(\frac{dx}{dH}\right)^2$$

(67)

When these equations are combined and added to corresponding equations for the loss in separative work in the heavy stream, there results for the total loss of separative work due to back diffusion per unit screen area, $W''/A$:

$$\frac{W''}{A} = \frac{RT_o(W_L \eta + W_H \eta)D_o \rho}{x(1-x)}\left(\frac{dx}{dH}\right)^2$$

(68)

Since $dx/dH = E dx/dA$, $f = L/E$ and $dx/dA$ is given by (51) the loss in separative work may be written as:

$$\frac{W''}{A} = \frac{N^2 RT_o(W_L \eta + W_H \xi)D_o \rho \gamma^2 x(1-x)}{f^2}\ \frac{b^2 c^2}{(a+b)^2}$$

(69)

The ratio of the loss in separative work caused by back diffusion to the separative work done by the screen is obtained by dividing $W''/A$ by $W/A$, from (44A):

$$\frac{W''}{W} = \frac{2N(W_L \eta + W_H \xi)(D_o \rho)}{f^2}\ \frac{b^2}{a+b}$$

(70)

In balanced diffusion, $N$ is given by

$$\frac{D_o \rho}{Z} \ln \xi/\eta$$

and $a$ and $b$ by (53.1) so that:

$$\frac{W''}{W} = \frac{(W_L \eta + W_H \xi)(D_o \rho)^2}{Z f^2}\ \frac{\ln \xi/\eta}{\frac{1}{\eta}-\frac{1}{\xi}+\left(\frac{D_o}{D_{12}}-1\right)\ln \xi/\eta}$$

(71)

An example will be given of the use of Equations (64) and (71) to set flow rate and clearances in separating $C^{12}H_4$ from $C^{13}H_4$ by diffusion in steam at atmospheric pressure. The conditions assumed given for the light and heavy streams are given in Table C.

**TABLE C**

| Stream | Light | Heavy |
|---|---|---|
| Mole fraction methane.. | 0.1 | 0.9 |
| Molecular weight ...... | $M_L=17.8$ | $M_H=16.2$ |
| Temperature, ° F. ..... | 210 | 125 |
| Molal density, lb.mole/ cu.ft. ............... | $\rho_L=0.00204$ | $\rho_H=0.00234$ |
| Viscosity $\times 10^6$, lb./(ft.) (sec.) ........... | $\mu_L=0.91$ | $\mu_H=0.81$ |
| $\rho D_o$, lb.mole/(ft.) (sec.). | | $7 \times 10^{-7}$ |

As an example, it is assumed that the screen is 0.048 in. (0.004 ft.) thick, and has 5% free area in the form of holes $10\mu$ ($3.28 \times 10^{-5}$ ft.) in diameter. The clearances should be kept as low as possible to minimize the diffusion length, $Z$. The heavy stream must, however, have a clearance of ½ in. ($W_H = 0.042$ ft.) or more, to provide drainage for condensate. If the light stream clearance is also taken as ½ in. ($W_L = 0.042$), the flow per unit width, $f$, should be $6.6 \times 10^{-5}$ lb. mole/(ft.)(sec.) from (64).

The effective diffusion length, $Z$, for laminar flow is:

$$Z = \frac{13}{35}(0.042 + 0.042) + \frac{0.004}{0.05} = 0.111 \text{ ft.}$$

Under these conditions, the fractional loss in separative work, from (71), is 0.001, which is satisfactorily low. In fact, $W_H$ and $f$ could each be taken smaller without introducing serious back diffusion, but this might lead to mechanical difficulties in maintaining uniform clearances in the heavy stream.

The pressure drop across the screen in this design example is calculated as follows. The permeability of the screen, defined by (5), is $3.035 \times 10^{-4}$ lb.mole/lb.sec. The molal velocity through the screen,

$$N = \frac{D_o \rho}{Z} \ln \xi/\eta$$

is $1.39 \times 10^{-6}$ lb.mole/(sq.ft.)(sec.) The pressure drop is the ratio of the second of these to the first, or 4.56 lb./sq.ft., or 0.88 in. of water.

Since the width of screen is given by $E = L/f$, it is seen that the optimum width in the stripping section is:

$$E_{opt} = \frac{B}{f}\left[1 + \frac{x-x_2}{x(1-x)}\frac{a+b}{c\gamma}\right]$$

(72)

Since $dx/dH = (L/f)dx/dA$, the differential equation for the optimum height is:

$$\left(\frac{dH}{dx}\right)_{opt.} = \frac{f(a+b)}{N\gamma x(1-x)bc}$$

(73)

The height of screen needed to enrich light component from $x_2$ to $x$ is obtained by integration:

$$H_{opt} = \frac{f(a+b)}{N\gamma bc}\ln \frac{x(1-x_2)}{x_2(1-x)}$$

(74)

For balanced diffusion with $\gamma << 1$ and $D_o = D_{12}$, these equations become:

$$E_{opt} = \frac{2B}{f\gamma \ln \xi/\eta}\frac{x-x_2}{x(1-x)}$$

(75)

and

$$H_{opt} = \frac{2fZ\left(\frac{1}{\eta}-\frac{1}{\xi}\right)}{D_o \rho \gamma \ln^2 \xi/\eta}\ln \frac{x(1-x_2)}{x_2(1-x)}$$

(76)

Figure 7 is a plot of the optimum height of screen versus optimum width for the methane separation example under consideration. The striking feature of this plot is the relatively large amount of screen area at the feed point, decreasing toward zero as the product ends of the plant are approached. The area under this curve is the total amount of screen in the plant, given in Table 2 as 43,020 sq.ft.

An actual diffusion separation plant would not be built as the single drastically tapered column illustrated by Figure 7. Instead, a large group of columns in parallel would be used at the feed point, with this group connected in series with other groups containing progressively fewer columns in parallel as the product ends of the plant were approached. For example, if the screen in each column were a circular cylinder 50 ft. high and 7.6 in. in diameter (width per column, 2.0 ft.), 81 columns in parallel would be used at the feed point. The next lower set of columns, in the 1570-1620 foot height interval, would contain 70 columns in parallel, etc. At the bottom of the plant a single column would suffice.

## Notation (Part 1)

$a$ = function of $\xi$ and $\eta$, Eq. (42.1)

$A$ = stage screen area, sq.ft.

$b$ = function of $\xi$ and $\eta$, Eq. (42.2)

$B$ = bottoms flow rate,* lb.mole/ sec.

$c$ = function of $\xi$ and $\eta$, Eq. (42.3)

$C_D$ = screen diffusivity, lb.mole/ (sq.ft.) (sec.), Eq. (6)

$C_P$ = screen permeability, lb.mole /(lb.) (sec.), Eq. (4)

$d$ = diameter of holes in screen, ft.

$D$ = tops flow rate,* lb.mole/sec.

$D_{ij}$ = diffusion coefficient of indicated pair of components, sq.ft./sec.

$D_o$ = mean diffusion coefficient, sq.ft./sec., Eq. (15)

$e$ = base of natural logarithms

$E$ = screen width, ft.

$f$ = flow rate per unit width,* lb.mole/(ft.)(sec.)

$f'$ = back diffusion rate per unit width,* lb. mole/(ft.) (sec.)

$F$ = feed rate,* lb.mole/(sec.)

$g$ = acceleration of gravity, 32.2 ft./(sec.)(sec.)

$G$ = mass velocity, lb./(sq.ft.) (sec.)

$H$ = screen height, ft.

$J$ = flow rate of separating agent, lb.mole/sec.

$L$ = downflow rate of heavy stream,* lb. mole/sec., Figs. 6 and 8

$M$ = molecular weight, lb./lb. mole
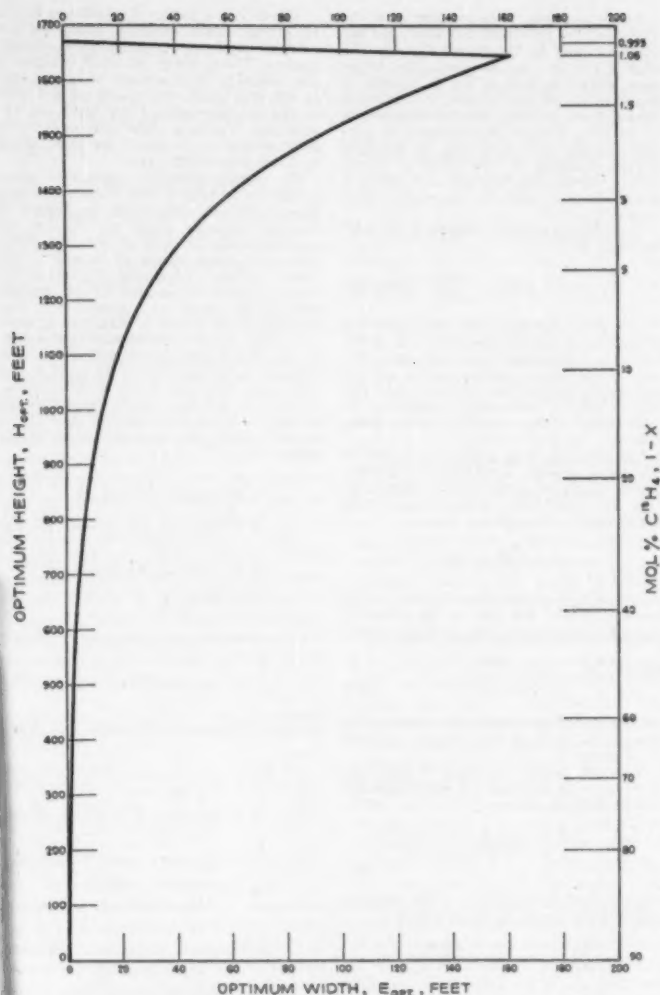
Fig. 7. Optimum dimensions of screen in mass diffusion column producing 100 g./day of C¹³

Purity = 90%; Feed concentration = 1.06%; Recovery = 10%.

$N$ = molal velocity, lb.mole/(sq. ft.) (sec.)

$P$ = pressure, lb./sq.ft.

$r$ = distance through screen, ft.

$R$ = gas constant, 1043 ft.lb./ (lb.mole) (° R.)

$Re$ = Reynolds number, $2WG/\mu$

$t$ = effective distance through screen, ft., $\int dr/\lambda$

$T_o$ = temp. at which heat is rejected, ° R.

$U$ = reduced molal velocity through screen, $NZ/D_o\rho$

$v$ = mole fraction light component* within hole of screen, Figure 5

$V$ = upflow rate of light stream,* Figs. 6 and 8

$W$ = clearance of duct, ft., Fig. 4

$W_s$ = thickness of screen, ft., Fig. 4

$W$ = rate of performing separative work, ft.lb./sec.

$W'$ = rate of loss of separative work due to back diffusion, ft.lb./sec.

$x$ = the mole fraction of light component in heavy stream on separating agent-free basis, Figs. 5 and 6

$x_i(x_j)$ = mole fraction of $i$th ($j$th) component

$y$ = the mole fraction of light component in light stream on separating agent-free basis, Figs. 5 and 6

$Z$ = effective diffusion length of screen and light and heavy streams, ft., $Z_L + Z_g/\lambda + Z_H$

$Z_H$ = diffusion length of heavy stream, ft.

$Z_L$ = diffusion length of light stream, ft.

$\gamma$ = separability, Eq. (14)

$\delta$ = function of molal velocities, Eq. (17)

$\epsilon$ = measure of composition difference between light and heavy streams, $\dfrac{y-x}{x(1-x)}$

$\eta$ = mole fraction of main components in light stream, Figs. 5 and 6

$\lambda$ = fraction of screen area open to flow

$\mu$ = function of diffusion coefficients and molal velocities, Eq. (32) and (34)

$\mu$ = viscosity, lb./ft.sec.

$\xi$ = mole fraction of main components in heavy stream, Figs. 5 and 6

$\pi(x_F, x_B)$ = separation potential for stripping section, Eq. (57)

$\pi(x_F, y_D)$ = separation potential for rectifying section, Eq. (59)

$\rho$ = molal density, lb.mole/cu.ft.

$\phi$ = mole fraction of main components within hole of screen, Fig. 5

Subscripts:

$_0$ = separating agent

$_1$ = light component, or hydrogen

$_2$ = heavy component

$_B$ = bottoms or stripping section

$_D$ = tops or rectifying section

$_F$ = feed

$_H$ = heavy stream

$_L$ = light stream

* On separating agent-free basis.

*The remainder of this article, describing the separation of isotopes in a cascade of mass diffusion stages and the extraction of hydrogen by mass diffusion, will appear in following issues of Chemical Engineering Progress.*

# SWEEP DIFFUSION GAS SEPARATION PROCESS[*]

## PART I

### MARIO T. CICHELLI,[†] W. D. WEATHERFORD, JR., and JOHN R. BOWMAN

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AMONG the methods available for separating the components of gaseous mixtures, low-temperature distillation, absorption, and adsorption are the commonly employed commercial means. Lately, considerable interest has been associated with the less common gas separation processes of thermal diffusion, gaseous effusion, and mass diffusion or atmolysis. Descriptions of each of these processes together with literature references are contained in a paper by Benedict (1).[‡] In brief, thermal diffusion is the process whereby a concentration gradient is set up in a gas mixture as a result of the presence of a temperature gradient in the gas. Gaseous effusion is the process whereby a concentration difference is set up on opposite sides of a fine-pored membrane because of differences in the rates of effusion through the membrane of the components.

In atmolysis, a readily condensable vapor is made to diffuse through a coarse-pored membrane opposite in direction to the diffusion of a gaseous mixture, and as a result, the component of the gas mixture having the higher diffusivity will appear in higher concentration on the side of the membrane at which the vapor enters. As Benedict points out, these less conventional processes are irreversible by nature, and are characterized by low thermodynamic efficiencies. However, in certain cases, one of these latter processes may be more economical or more desirable than the conventional processes because of one or more of the following reasons: (1) simpler construction, (2) simpler operation under more moderate conditions, (3) lower holdup of valuable material, and (4) more favorable separation factor.

[*] Contribution from Gulf Research & Development Co.'s Multiple Fellowship, Mellon Institute.
[†] Present address: Du Pont Co.
[‡] Literature Cited will be published in a forthcoming issue of "C.E.P."

In this paper a new gas separation process is described which has been given the name "sweep diffusion." In the sweep diffusion process, a readily condensable vapor is made to diffuse through a mixture of gases toward a condensing surface. This flowing vapor carries or "sweeps" toward the condensing surface those components of the gas which have lower rates of diffusion through the vapor.

Figure 1 shows the bare essentials of a continuous, single-stage sweep diffusion unit. A condensable vapor and a feed gas consisting of a mixture of two or more components enter the enclosure, one surface of which (in this case, the bottom) is cold. The vapor diffuses through the gas mixture and condenses on the cold surface. Two product gas streams are withdrawn from the enclosure, one farther from the condensing surface than the other. The stream farthest from the condensing surface is enriched in one component of the gas mixture while the other stream is enriched in a second component whose diffusivity through the vapor

is less than the first component. This second component may be said to be "less diffusible" through the vapor than the first component, and it is, in effect, carried, or "swept," to the condensing surface in greater proportion than the more diffusible component.

Although a readily condensable vapor is usually the most satisfactory sweeping agent, any material which can be easily removed from the gaseous phase by processes such as freezing, absorption, chemical reaction or adsorption can function in this capacity.

Aerosols, such as smokes, may be concentrated or precipitated by the sweep diffusion process.

In general the single-stage process would be impractical for gas separation because of the small degree of enrichment ordinarily obtained. The enrichment can be increased either by connecting a number of such stages in cascade, or preferably, by causing two gas streams to flow countercurrent to each other, one of the streams being farther from the condensing surface than the other and in this way producing a column process.
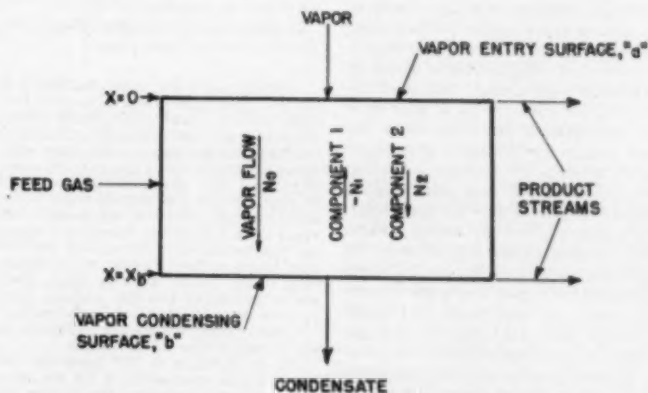


Fig. 1. Cross section of single-stage sweep diffusion unit.

FEED GAS

VAPOR FEED

TOP PRODUCT

LIQUID FEED

LIQUID DISTRIBUTOR

ENRICHING SECTION

LIQUID GUIDE TUBE

LIQUID CURTAIN

FEED ENTRY TUBE

STRIPPING SECTION

GAS STREAM ENRICHED WITH RESPECT TO MORE DIFFUSIBLE COMPONENT

LIQUID CURTAIN

LIQUID GUIDE TUBE

VAPOR

A

ENLARGED VIEW

POROUS VAPOR ENTRY TUBE

GAS STREAM ENRICHED WITH RESPECT TO LESS DIFFUSIBLE COMPONENT

BOTTOM PRODUCT

EFFLUENT LIQUID

FRONT VIEW

FEED ENTRY TUBE

VAPOR ENTRY TUBE

LIQUID GUIDE TUBE

SECTION A-A

Fig. 2. Schematic drawing of sweep diffusion column.

Although numerous devices may be employed to produce the desired countercurrent flow, it has been found convenient to utilize a liquid stream flowing downward on a vertical surface to serve in the dual capacity of a vapor-condensing surface and a means for producing a downward flow of the gas immediately adjacent to it. Figure 2 is a schematic drawing of such a sweep diffusion column, in this case having a concentric tube arrangement for vapor entry and vapor condensing surfaces. The column shown consists of both an enriching section (above the feed point) and a stripping section (below the feed point). The porous vapor entry tube is located inside the liquid curtain guide tube, the annular space between the two cylinders serving as the region where gas separation occurs. A feed entry tube inside the vapor entry tube permits feed gas mixture to be introduced into the annular separating space at a position in the column where the gas composition is the same as the composition of the feed. A

liquid distributor located at the top of the outer tube permits uniform distribution of the liquid flowing down the inside wall of this tube. The exposed surface of the liquid curtain so formed is the vapor condensing surface.

During operation of the column, the following actions take place.

A liquid enters the liquid distributor at the top of the column, and is made to flow down the inside wall of the liquid curtain guide tube in a continuous film. A readily condensable vapor enters at the vapor inlet, passes downward into a coarse-pored vapor entry tube, and passes radially outward through the tube and annular space to the liquid curtain, where it condenses. The vapor entry tube serves merely as a means for introducing vapor throughout the column length without causing undue turbulence in the annular working space. Feed gas is introduced into the working space at some point of elevation in the column, and gas product streams are withdrawn at the top and bottom of the column.

At any elevation in the apparatus, the less diffusible component of the gas mixture is present in higher concentration, on a vapor-free basis, near the condensing sur-

face. The downward flowing liquid curtain drags with it the gas immediately adjacent to it. In the section of column above the feed gas inlet, at steady state, there will be an upflow of gas at any elevation equal to the sum of the downflow rate at that elevation and the top product flow rate. This gas stream flows upward near the outside wall of the vapor entry tube. At the top of the column, therefore, part of the upflowing gas stream reverses its direction and flows downward adjacent to the liquid film while the rest flows out of the apparatus as top product. A similar action takes place at the bottom of the column. Part of the downflowing gas stream reverses its direction and flows upward near the vapor entry tube while the rest flows out of the apparatus as bottom product.

Because of the cross-flowing vapor, the gas stream flowing downward near the water film is continually enriched in the less diffusible component in its progress down the tube while the gas stream flowing upward near the vapor entry tube is continually enriched in the more diffusible component in its progress up the tube. In effect, the operation of this apparatus may be considered as analogous to taking the single-stage unit of Figure 1, turning it on its side, and causing the gas in the enclosure to flow in two streams countercurrent to each other. In this manner, the single-stage process of Figure 1 may be converted into a column process, and, as in rectification, increasing the length of the column improves the separation.

There are several obvious possible modifications in the basic design shown in Figure 2. For example, an outside jacket could be used for cooling the liquid curtain, a parallel plate arrangement could be used rather than concentric tubes, and the relative positions of the concentric liquid curtain guide tube and vapor entry tube could be reversed. For difficult separations, long tubes may be used, connected to each other in series if necessary. To achieve a large capacity, a number of identical tubes may be connected together in parallel in a tube bundle arrangement.

## Theoretical

The theoretical treatment begins with the development of equations for the concentration profiles in a single-stage sweep diffusion process, passes on to the sweep diffusion column process, and ends with an extension of the theory of the column process to the case of the "tapered" plant. The theory has been restricted to the separation of binary gas mixtures by means of a single sweep vapor. It has also been assumed that the gases in the separating zone obey the perfect gas laws.

*Single-Stage Apparatus.* Figure 1 shows the diffusional flow streams in a parallel plane, single-stage sweep diffusion unit. In the case where there is no flow of gas or vapor in a direction parallel to the vapor entry or condensing surfaces and equilibrium conditions prevail, the vapor diffuses through a
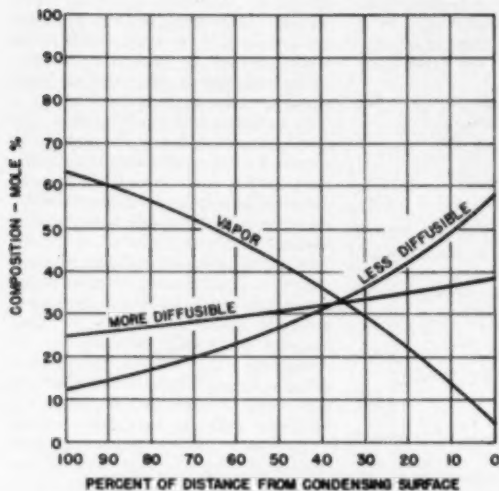
Fig. 3. Composition diagram for single-stage sweep diffusion unit.
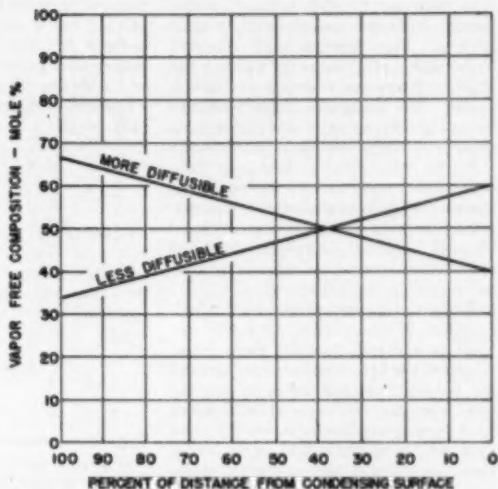


Fig. 4. Composition diagram on vapor-free basis for single-stage sweep diffusion unit.

stagnant gas mixture and $N_1$ and $N_2$ are therefore both equal to zero.

The Maxwellian (9) equations for the diffusion of a gas through a mixture of two other gases are:

$$-\frac{\partial p_1}{\partial x} = \frac{RT}{D_{12}P}(N_1 p_2 - N_2 p_1)$$
$$+ \frac{RT}{D_{01}P}(N_1 p_0 - N_0 p_1) \quad (1)$$

$$-\frac{\partial p_2}{\partial x} = \frac{RT}{D_{12}P}(N_2 p_1 - N_1 p_2)$$
$$+ \frac{RT}{D_{02}P}(N_2 p_0 - N_0 p_2) \quad (2)$$

$$-\frac{\partial p_0}{\partial x} = \frac{RT}{D_{01}P}(N_0 p_1 - N_1 p_0)$$
$$+ \frac{RT}{D_{02}P}(N_0 p_2 - N_2 p_0) \quad (3)$$

Setting $N_1$ and $N_2$ equal to zero, Equation (1) yields

$$-\frac{\partial p_1}{\partial x} = \frac{p_1 N_0 RT}{D_{01}P} \quad (4)$$

Integration of Equation (4), holding $T$ constant, yields

$$p_1 = p_{1b} e^{\frac{N_0 RT(x-x_b)}{D_{01}P}} \quad (5)$$

Similarly, $p_2$ is given by

$$p_2 = p_{2b} e^{\frac{N_0 RT(x-x_b)}{D_{02}P}} \quad (6)$$

Considering a known mixture of gases being separated by a given sweep vapor, the composition profile for each component may readily be calculated, given $p_{0b}$, $P$, $T$, $N_0$, $D_{01}$, $D_{02}$, and $y_F$. The value of $p_{0b}$ is the vapor pressure of the condensate. From the perfect gas laws,

$$p_1 = y(P - p_0) \quad (7)$$

$$p_2 = P - p_1 - p_0 \quad (8)$$

and

$$y_1 = \frac{p_1}{P}, \ y_2 = \frac{p_2}{P}, \ y_0 = \frac{p_0}{P} \quad (9)$$

At equilibrium in the single-stage apparatus, the ratio of the moles of more diffusible component to less diffusible component across an element of volume having a length equal to $x_b$ is the same as the ratio in the feed gas. Thus,

$$\frac{\int_0^{x_b} y_1 dx}{\int_0^{x_b} y_2 dx} = \frac{y_F}{1 - y_F} \quad (10)$$

Substituting Equations (5) and (6) into (9), and the result into (10), yields upon integrating and rearranging

$$\frac{p_{1b}}{p_{2b}} = \frac{y_F D_{02}\left(1 - e^{-\frac{N_0 RT x_b}{D_{01}P}}\right)}{(1 - y_F) D_{01}\left(1 - e^{-\frac{N_0 RT x_b}{D_{02}P}}\right)} \quad (11)$$

From Equation (11), the ratio of $p_{1b}/p_{2b}$ is determined and the result is combined with Equation (8) (in which $P$ and $p_{0b}$ are known) to yield the values of $p_{1b}$ and $p_{2b}$. Equations (5) and (6) are then used to obtain $p_1$ and $p_2$ at several values of $x$, and by use of Equations (9), curves may be drawn of mole fraction of each component versus the distance, $x$, from the vapor entry surface.

Figure 3 shows a set of composition profiles for the separation of a mixture of hydrogen and methane using steam as the sweep vapor. The conditions used in calculating the curves shown in Figure 3 were as follows: $y_F = 0.51$, vapor entry temperature = 220° F. vapor condensing temperature = 90° F., steam diffusion rate = 2.76 × 10⁻⁵ g.moles/(sq.cm.)(sec.), pressure = 1.217 atm. and $x_b = 0.6$ cm. The diffusivity of steam through methane was calculated using Gilliland's (4) equation:

$$D_{02} = \frac{0.0043 T^{1.5}\sqrt{\frac{1}{M_2} + \frac{1}{M_0}}}{P(V_2^{1/3} + V_0^{1/3})^2} \quad (12)$$

The value for the diffusivity of steam through hydrogen was obtained by multiplying the International Critical Tables value at $0°$ C. by the ratio of the absolute temperatures raised to the 1.5 power. The arithmetic mean temperature of the vapor entry and vapor condensing surfaces was used throughout.

Figure 4 is a plot of the mole fraction of each gas on a vapor-free basis versus the percentage of the distance from the vapor condensing surface. Though apparently straight, the lines are actually curved, as may be proved by combining Equations (5), (6), (7), and (8) eliminating all variables except $y$ and $x$. Differentiation of $y$ with respect to $x$ reveals that the slope is not constant, but is a function of $x$. Setting the second derivative equal to zero locates a point of inflection on both curves in Figure 4 at their intersection (i.e., at $y = 0.5$). Examination of the equations shows that this inflection point is a point of steepest slope in both curves. If the curves do not cross each other, such as would occur when the bulk gas composition is rich in one or the other component, then they do not pass through a point of inflection. Curves and portions of curves above the line where $y = 0.5$ are concave downward, while curves and portions of curves below $y = 0.5$ are concave upward.

*Single-Stage Separation Factor.* The separation factor in gas separation processes is analogous to the relative volatility in distillation. In the distillation of binary mixtures, the relative volatility has been defined as the ratio of the mole ratio of the more volatile component in the vapor to its mole ratio in a liquid in equilibrium with the vapor. In gas separation processes employing diffusion in the gaseous phase, the separation factor is the ratio of two mole ratios of gas mixtures which are in a steady-state condition, but instead of the mixtures of different compositions being in different *phases*, as in distillation, they are instead in different *locations*. The separation factor in thermal diffusion, gaseous effusion, mass diffusion, and sweep diffusion is the ratio of the mole ratio of the more diffusible component of the gas mixture at one location to its mole ratio at another location at steady state. In the single-stage sweep diffusion apparatus, the analogy of thermal diffusion has been carried over, and the locations chosen for definition of $a°$, the single-stage point separation factor, are the vapor-entry surface and the vapor-condensing surface respectively. Thus,

$$a° = \frac{(y_a°)(1 - y_b°)}{(y_b°)(1 - y_a°)}$$

(13)

where $a°$ is defined for conditions under which there is no diffusion of 1 or 2 in the $x$ direction, and there is no convective flow parallel to the vapor entry or condensing surfaces.

Combining Equations (7), (8), and (13), yields

$$a° = \frac{(p_{1a})(p_{2b})}{(p_{1b})(p_{2a})}$$

(14)

Evaluating $(p_{1a})/(p_{1b})$ by substituting $x = 0$ into Equation (5), and similarly, $(p_{2a})/(p_{2b})$ by substituting $x = 0$ into Equation (6), the single-stage point separation factor is found to be

$$a° = e^{\frac{v_b N_0 RT}{P}\left(\frac{1}{D_{01}} - \frac{1}{D_{02}}\right)}$$

(15)

For the numerical example presented above, $a° = 2.94$.

In the single-stage process, there will usually be a temperature gradient in the $x$ direction resulting in a superposed thermal diffusion separation and also a variation of $D$ and $T$ with $x$ in Equations (1)-(4). Calculations made wherein these effects were included indicate that they are secondary in magnitude to the separation predicted by isothermal molecular diffusion and are usually in such a direction as to predict a somewhat better separation than when they are neglected. The correction due to variation of $D$ and $T$ with $x$ in the diffusion equations is normally so small as to be of negligible importance. In some cases, the thermal diffusion correction may be appreciable, and detailed consideration is given to this in the theoretical development for the column process.

In actual operation of a single-stage unit of the type shown in Figure 1, product streams are withdrawn, and there is flow of gas parallel to the vapor entry and condensing surfaces. In this case, the composition profile beyond a certain distance from the feed entry point will be the same as for the case of no flow developed above. The product streams withdrawn would not have compositions equal to $y_a°$ and $y_b°$, however. Instead they would have compositions corresponding to average values of $y$ over regions near the boundaries.

*Column Process*

In the column process, besides establishing a flow of vapor from an entry surface to a vapor-condensing surface, it is necessary to cause the gas adjacent to these surfaces to flow in streams countercurrent to each other. The theory has been developed for the case in which the countercurrent flow is developed by means of a flowing liquid curtain. Inspection of the pertinent equations will show what modifications would have to be made for the case where other means of producing countercurrent flow are used.

R. C. Jones and W. H. Furry (6) have treated in detail the theory of operation of thermal diffusion columns. Development of the theory of the sweep diffusion column process has in many places been made to follow the pattern used by Jones and Furry.

In sweep diffusion columns, the existence of a temperature gradient in the $x$ direction causes additional separation, generally small, because of the phenomenon of thermal diffusion. In the development that follows, the thermal diffusion effect will be treated after the more important equations for separation by sweep diffusion have been treated.

Turbulence in the separating zone tends to destroy whatever concentration gradients have been set up in the working space, and the theory is therefore limited to the case where laminar flow prevails. As for the single-stage treatment, the argument is restricted to the separation of a binary-gas mixture, and it is assumed that the gas-vapor mixture follows the perfect gas laws. The parallel plane case is considered first.

*Derivation of the Transport Equation.* In a sweep diffusion column operating under steady-state conditions, a material balance on the more diffusible component of the gas at any elevation above the feed point yields:

$$Dy_D = L(y^I - y^{II}) + Dy - \tau_{1,d}$$

(16)

where $L$ is the convective downflow of vapor-free gas, $y^I$ and $y^{II}$ are the mean mole fractions of the more diffusible component on a vapor-free basis in the upflowing and downflowing streams respectively, and $\tau_{1,d}$ is the longitudinal diffusion of the more diffusible component down the column due to its concentration gradient. Equation (16) is the transport equation, or the equation of the operating line, for the enriching section of a sweep diffusion column. The first term on the right-hand side of Equation (16) is the net upflow of more diffusible component resulting from the difference in composition of the two streams, the second term is the upflow of this component due to the presence of a net vapor-free gas upflow rate equal to $D$ in the enriching section of the column, and the last term is the downward diffusion of more diffusible component due to the concentration gradient in the $z$ direction. A similar relation applies below the feed point.

The aim of the development that follows is to reduce Equation (16) to a

group of variables that can readily be evaluated experimentally, and then to solve the equation, so that it will be possible to relate the separation obtained in a column of certain dimensions, to the operating conditions of temperature, pressure, feed rate, feed composition, liquid curtain rate, and vapor rate.

*Evaluation of the Longitudinal Diffusion Term.* Equation (1) may be used to evaluate $\tau_{1,d}$ by replacing $x$ by $z$, setting $N_{0_2}$ equal to zero, and letting $N_1 = -N_{2_z}$. Thus,

$$\tau_{1,d} = -N_{1_z} x_b \overline{E} =$$

$$\frac{P x_b \overline{E}}{RT\left[\dfrac{1}{D_{12}} + \dfrac{p_0}{(P-p_0)D_{01}}\right]}\frac{\partial y}{\partial z}$$

(17)

The coefficient of $\partial y/\partial z$ in Equation (17) could be evaluated if the true mean value of $\overline{p_0}$, averaged across the working space, were known. Since, in properly designed columns, $\tau_{1,d}$ is much less than $L(y^I - y^{II})$, a rather rough mean value of $p_0$ can be used without sacrificing any appreciable accuracy in Equation (16). Thus, the value of $p_0$ and $E$ at $x = 0.5x_b$ is satisfactory for Equation (17). Also, the absolute magnitudes of the net horizontal flow of the components of the gas are much smaller than that of the vapor, and hence it is satisfactory to use Equation (3) with $N_1$ and $N_2$ set equal to zero to evaluate the partial pressure of vapor at any $x$. Therefore,

$$-\frac{\partial p_0}{\partial x} = \frac{\partial(P-p_0)}{\partial x}$$

$$= \frac{N_0 RT(P-p_0)}{P}\left(\frac{y}{D_{01}} + \frac{1-y}{D_{02}}\right)$$

(18)

Rearranging Equation (18) and integrating between $0.5x_b$ and $x_b$, holding $y$ constant at a mean value, yields,

$$\overline{P-p_0} = \frac{P-p_{0_b}}{\sqrt{s}}$$

(19)

where

$$s = e^{\frac{x_b N_0 RT}{P}\left(\frac{\overline{y}}{D_{01}} + \frac{\overline{1-y}}{D_{02}}\right)}$$

(20)

and $\overline{y}$ is taken as the average value between the composition at the feed point and in the product. A rough estimate of $\overline{y}$ is adequate for use in Equation (20). The value of $\overline{p_0}$ is simply:

$$p_0 = P - \overline{P - p_0}$$

(21)
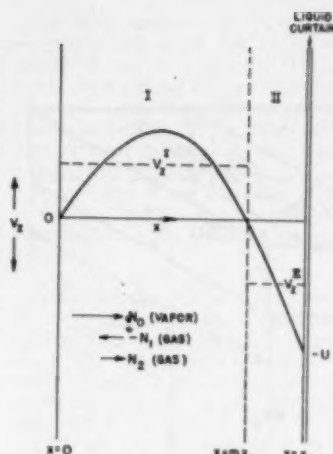


Fig. 5. Flow of gases and vapors in sweep diffusion column.

Substituting Equations (19) and (21) into (17) affords

$$\tau_{1,d} = K_d \frac{\partial y}{\partial z}$$

(22)

where

$$K_d = \frac{P x_b \overline{E}}{RT\left[\dfrac{1}{D_{12}} + \dfrac{P(\sqrt{s}-1)+p_{0_b}}{(P-p_{0_b})D_{01}}\right]}$$

(23)

Under ordinary operating conditions the magnitude of the longitudinal diffusion term ($\tau_{1,d}$) is negligible.

*Determination of* $(y^I - y^{II})$. Evaluating $y^I$ and $y^{II}$ at any elevation at points $0.5x_b$ cm. apart (see Fig. 5), one obtains the approximation:

$$y^I - y^{II} = -0.5x_b\left[\frac{\partial y}{\partial x}\right]_{x = 0.5x_b}$$

(24)

In justification of the assumption that the positions corresponding to the mean compositions of the upflowing and downflowing streams are $0.5x_b$ cm. apart, a sample computation was made, and the error was found to be less than 1%. If $y$ varies linearly with $x$, as is nearly true in the single-stage apparatus (see Fig. 4), then Equation (24) is

exact, otherwise, it is a close approximation. The evaluation of $\partial y/\partial x$ at the position of no vertical flow (at $x = m_s x_b$) would be more accurate but considerably more cumbersome than the recommended evaluation at $0.5x_b$. Analysis of the appropriate equations shows that the recommended procedure is slightly conservative.

The problem now reduces to determining the value of $\partial y/\partial x$. Solving Equation (7) for $y$, differentiating with respect to $x$, and simplifying,

$$\frac{\partial y}{\partial x} = \frac{1}{P-p_0}\frac{\partial p_1}{\partial x} + \frac{y}{(P-p_0)}\frac{\partial p_0}{\partial x}$$

(25)

Since at steady state $L$ and $\dot{V}$ are fairly constant along the column, there can be no net flow of vapor-free gas from one stream to the other. That is to say, $N_1$ must equal $-N_2$. Making use of this relationship, substitution of Equations (1) and (3) into Equation (25) yields

$$\frac{\partial y}{\partial x} = -\frac{N_1 RT}{P}\left[\frac{1}{D_{12}} + \frac{p_0}{(P-p_0)D_{01}}\right]$$
$$+ \frac{N_0 RTy}{PD_{01}} - \frac{N_0 RTy}{P}\left(\frac{y}{D_{01}} + \frac{1-y}{D_{02}}\right)$$
$$- \frac{N_1 RTp_0 y}{P(P-p_0)}\left(\frac{1}{D_{02}} - \frac{1}{D_{01}}\right)$$

(26)

Combining $N_1$ terms and $N_0$ terms,

$$\frac{\partial y}{\partial x} = -$$

$$\frac{N_1 RT}{P}\left[\frac{1}{D_{12}} + \frac{p_0}{P-p_0}\left(\frac{1-y}{D_{01}} + \frac{y}{D_{02}}\right)\right]$$
$$- \frac{N_0 RT}{P}\left[\frac{1}{D_{02}} - \frac{1}{D_{01}}\right]y(1-y)$$

(27)

Referring to Figure 6 at steady state, a material balance on a differential length of column yields

$$-N_1 E dz = L \frac{\partial y^{II}}{\partial z} dz$$

(28)

The variation of $\partial y/\partial z$ with respect to $x$ is a second order effect of negligible significance, and Equation (28) may therefore be rewritten

$$N_1 = -\frac{L}{E}\frac{\partial y}{\partial z}$$

(29)

Substituting Equation (29) into (27) and combining the result with Equation (24), one obtains

$$y^I - y^{II} = \frac{0.5x_b N_0 RT}{P}\left[\frac{1}{D_{02}} - \frac{1}{D_{01}}\right]y(1-y)$$

$$- \frac{0.5x_b LRT}{EP}\left[\frac{1}{D_{12}} + \frac{\overline{p_0}}{P-p_0}\left(\frac{\overline{1-y}}{D_{01}} + \frac{\overline{y}}{D_{02}}\right)\right]\frac{\partial y}{\partial z}$$

(30)
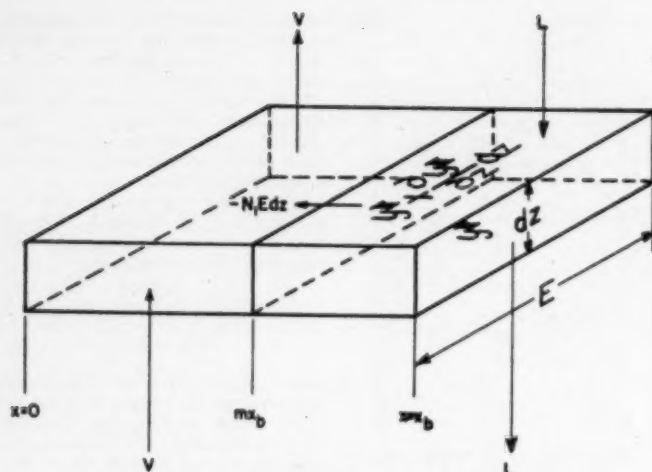
Fig. 6. Analysis of flows in differential length of column.

where $\overline{p_0}$ and $\overline{P - p_0}$ are evaluated at $x = 0.5x_b$, using Equations (19), (20), and (21); and $\overline{y}$ and $\overline{1 - y}$ are again the average values between the composition at the feed point and in the product. Use of these average values results in negligible error in the finally integrated equation.

*Transport Equation Neglecting Thermal Diffusion.* Equations (22) and (30) may now be substituted into equation (16) to yield

$$Dy_D = H_g y(1 - y) + Dy$$
$$- (K_e + K_d) \frac{\partial y}{\partial z} \quad (31)$$

where

$$H_g = \frac{0.5x_b L N_0 RT}{P} \left( \frac{1}{D_{02}} - \frac{1}{D_{01}} \right) \quad (32)$$

$$K_e = \frac{0.5x_b L^2 RT}{\overline{E} P} \left[ \frac{1}{D_{12}} + \frac{\overline{p_0}}{P - p_0} \left( \frac{\overline{1 - y}}{D_{01}} + \frac{\overline{y}}{D_{02}} \right) \right] \quad (33)$$

and $K_d$ is given by Equation (23).

The similarity of Equation (31) to the transport equation for thermal diffusion columns (6) is obvious. The difference lies in the values of the parameters $H_g$, $K_e$, and $K_d$.

*Evaluation of the Downflow Rate, L.* To obtain the downflow rate of vapor-free gas, $L$, in terms of readily measurable quantities, it is necessary first to establish the velocity profile across the sweep diffusion working space. Since the gravitational head and the energy terms are negligible and laminar flow prevails, the difference in shear across

an element of gas-vapor mixture of width $d_x$ is counterbalanced by the pressure drop across the element in the $z$ direction. Thus,

$$\mu \frac{\partial^2 v_z}{\partial x^2} = \frac{\partial P}{\partial z} \quad (34)$$

At any elevation, the total pressure is practically independent of $x$. Equation (34) may be integrated to yield

$$v_z = \frac{x^2}{2\mu} \frac{\partial P}{\partial z} + c_1 x + c_2 \quad (35)$$

The following boundary conditions may be used to evaluate $c_1$, $c_2$, and $\partial P/\partial z$:

$$\text{at } x = 0, \quad v_z = 0,$$
$$\text{at } x = m x_b, \quad v_z = 0,$$
$$\text{at } x = x_b, \quad v_z = -U \quad (36)$$

where $U$ is the linear velocity of the gas at the gas-liquid interface, and $x = m x_b$ is the location of the plane of no vertical flow between $x = 0$ and $x = x_b$.

Substituting (36) into (35) yields the following parabolic equation for the velocity profile:

$$v_z = \frac{U(m x_b x - x^2)}{x_b^2(1 - m)} \quad (37)$$

Figure 5 shows a typical velocity profile at some elevation in a sweep diffusion column. The downflow rate $L$ is given by:

$$L = \frac{E^{II}}{RT} \int_{mx_b}^{x_b} (P - p_0)(-v_z) dx$$

$$= \frac{E^{II}}{RT} (P - p_0)^{II} \int_{mx_b}^{x_b} (-v_z) dx \quad (38)$$

To simplify the solution, a mean value for $(P - p_0)$, designated as $(P - p_0)^{II}$ is used. This is taken as the value of $(P - p_0)$ at the point midway between $x = m x_b$ and $x = x_b$. Integrating Equation (18) between the limits $x_b(1 + m)/2$ and $x_b$ to obtain this midpoint value yields

$$(P - p_0)^{II} = \frac{P - p_{0_b}}{s^{0.5(1 - m)}} \quad (39)$$

where $s$ is defined by Equation (20). Substituting Equations (37) and (39) into Equation (38) and integrating yields

$$L = \frac{x_b E^{II} U(P - p_{0_b})(2 + m)(1 - m)}{6RT(s^{0.5(1 - m)})} \quad (40)$$

where for the parallel plane case, $E^{II} = E_a = E_b$.

The problem is now reduced to the evaluation of $U$ and of $m$.

*Evaluation of U.* To evaluate $U$, three assumptions are made: (1) the liquid curtain surface is smooth and devoid of ripples or waves, (2) there is no slippage at the liquid-gas interface, and (3) the velocity profile in the *liquid* phase is unaffected by the drag of the gas at the liquid-gas interface. The Reynolds number for the liquid is defined by:

$$Re_l = \frac{4w}{\mu_l E_b} \quad (41)$$

Since turbulence in the liquid film occurs at a Reynolds numbers of about 2100 (2), the following equations result.

*Viscous Flow; $Re_l < 2100$*

For viscous flow, the average velocity of the liquid film (2, 5, 10) is given by:

$$v_l = \frac{\rho g l^2}{3\mu_l} \quad (42)$$

where $l$, the film thickness, is equal to $w/\rho v_l E_b$. Likewise, for viscous flow, a parabolic velocity distribution prevails in the liquid curtain, with the maximum velocity, $U$, equal to 1.5 $v_l$. Making these substitutions in Equation (42), one obtains

$$U = 1.5 \left( \frac{g w^2}{3\mu_l \rho E_b^2} \right)^{\frac{1}{3}} \quad (43)$$

A more accurate value (than 1.5) for the ratio of the interfacial velocity to the mean liquid velocity may be used for Reynolds numbers in the range 25 to 350 (3, 5).

## Turbulent Flow; $Re_b > 2100$

In the turbulent range, $v_t$ may be calculated (2) by the ordinary Fanning equation, letting $dF/dN = 1$ for gravity flow. Thus,

$$v_t = \left(\frac{2gw}{f\rho E_b}\right)^{\frac{1}{2}} \quad (44)$$

where $f$, the Fanning friction factor, is a function of $Re_b$, and may be taken from a standard plot of $f$ vs. $Re$ (10). Inspection of curves for the isothermal velocity profile in turbulent flow (10) indicates that a good approximation for the maximum, or interfacial velocity, $U$, is $U = 1.1 v_t$. Substituting this into Equation (44) yields

$$U = 1.1\left(\frac{2gw}{f\rho E_b}\right)^{\frac{1}{2}} \quad (45)$$

*Evaluation of $m$.* In order to evaluate $m$, the fraction of the distance towards the vapor-condensing surface at which there is no vertical flow, it is necessary to make use of a material balance on the vapor-free gas in the column. Considering the enriching section of a column operating at steady state with top product gas being drawn off at the rate $D$, a material balance on the gas at any cross section yields:

$$\int_0^{mx_b} \frac{E(P-p_0)v_z}{RT}\,dx$$

$$+ \int_{mx_b}^{x_b} \frac{E(P-p_0)v_z}{RT}\,dx = D \quad (46)$$

or,

$$(P-p_0)^I \int_0^{mx_b} v_z dx$$

$$+ (P-p_0)^{II} \int_{mx_b}^{x_b} v_z dx = \frac{DRT}{E} \quad (47)$$

Taking the mean values of $(P-p_0)$ at the midpoints of streams $I$ and $II$, one obtains from Equation (18)

$$(P-p_0)^I = \frac{P-p_{0b}}{s^{1-\frac{m}{2}}} \quad (48)$$

$(P-p_0)^{II}$ is given by Equation (39). Equations (37), (39), and (48) are substituted into (47), which is then integrated to yield

$$\frac{1}{s^{0.5(1-m)}} =$$

$$\left[\frac{m^3}{1-m}\left(\frac{1}{\sqrt{s}}-1\right)+\frac{3m-2}{1-m}\right]$$

$$= \frac{6DRT}{U\overline{E}x_b(P-p_{0b})} \quad (49)$$

The same equation applies to the stripping section except that $(-B)$ is substituted for $D$ in Equation (49). Figure 7 was constructed from Equation (49), and it enables one to read off $m$ (which is identical to $m'$ for the parallel plane case) when the other quantities in Equation (49) are given.

From Figure 7, and Equations (43) or (45), $m$ and $U$ are obtained and substituted into (40) for final evaluation of $L$.

*Consideration of Thermal Diffusion.* Although normally the separation achieved in a sweep diffusion column due to the thermal diffusion effect is relatively small, it was considered advisable to determine theoretically the magnitude of this effect.

Equations (1)-(3) relate the partial pressure gradient for each component of a three-component gas mixture to the diffusion of these components in the $x$ direction. Where there is a temperature gradient in the $x$ direction, Equations (1) and (3) are extended as follows:

$$-\frac{\partial p_1}{\partial x} = \frac{RT}{D_{12}P}(N_1 p_2 - N_2 p_1)$$

$$+ \frac{RT}{D_{01}P}(N_1 p_0 - N_0 p_1)$$

$$- \frac{a^*_{12}y(1-y)(P-p_0)^2}{P}\frac{\partial \ln T}{\partial x}$$

$$- \frac{a^*_{10}y p_0(P-p_0)}{P}\frac{\partial \ln T}{\partial x} \quad (50)$$

$$-\frac{\partial p_0}{\partial x} = \frac{RT}{D_{01}P}(N_0 p_1 - N_1 p_0)$$

$$+ \frac{RT}{D_{02}P}(N_0 p_2 - N_2 p_0)$$

$$- \frac{a^*_{01}y p_0(P-p_0)}{P}\frac{\partial \ln T}{\partial x}$$

$$- \frac{a^*_{02}(1-y)p_0(P-p_0)}{P}\frac{\partial \ln T}{\partial x} \quad (51)$$

where $a^*$ is the thermal diffusion constant. The value of $a^*_{12}$ is positive if thermal diffusion causes component 1 to concentrate in the hotter zone and negative in the reverse case. Where available, experimental values for the thermal diffusion constant should be used. If experimental values are not available, an estimate of the thermal diffusion constant may be made by applying Jones and Furry's simplification of the Chapman equation, which defines $a^*$ as follows:

$$a^*_{12} = \frac{105}{118}\frac{M_2-M_1}{M_2+M_1}R_T = -a^*_{21} \quad (52)$$

where $R_T$ is the ratio of the actual value of the thermal diffusion constant to the value it would have for hard spherical molecules. $R_T$ is usually positive; however, in rare instances where $R_T$ is negative, the higher molecular weight material is concentrated in the hotter zone. Inspection of experimental values of $R_T$ obtained on gas mixtures similar to those under consideration enables estimating a value of $R_T$ for use in Equation (52).

To include the effect of thermal diffusion, Equations (50) and (51) are substituted into Equation (25), letting $N_1 = -N_2$, as before. The result is combined with Equation (24) and this latter result is substituted into Equation (16). The transport equation obtained, including the effect of thermal diffusion is

$$Dy_D = H_s y(1-y) + Dy - K\frac{\partial y}{\partial x}$$

$$- \frac{0.5x_b Ly(1-y)[\overline{p_0}(a^*_{10}-a^*_{20})+(\overline{P-p_0})a^*_{12}]}{P}\frac{\partial \ln T}{\partial x} \quad (53)$$

where

$$K = K_s + K_d \quad (54)$$

Making use of the approximation, $\partial \ln T/\partial x = -(T_d - T_b)/x_b\overline{T}$, where $\overline{T}$ is the arithmetic mean temperature, Equation (53) may be rewritten

$$Dy_D = Hy(1-y) + Dy - K\frac{\partial y}{\partial x} \quad (55)$$

where

$$H = H_s + H_T \quad (56)$$

and

$$H_T = \frac{0.5L(T_d-T_b)[\overline{p_0}(a^*_{10}-a^*_{20})+(\overline{P-p_0})a^*_{12}]}{P\overline{T}} \quad (57)$$
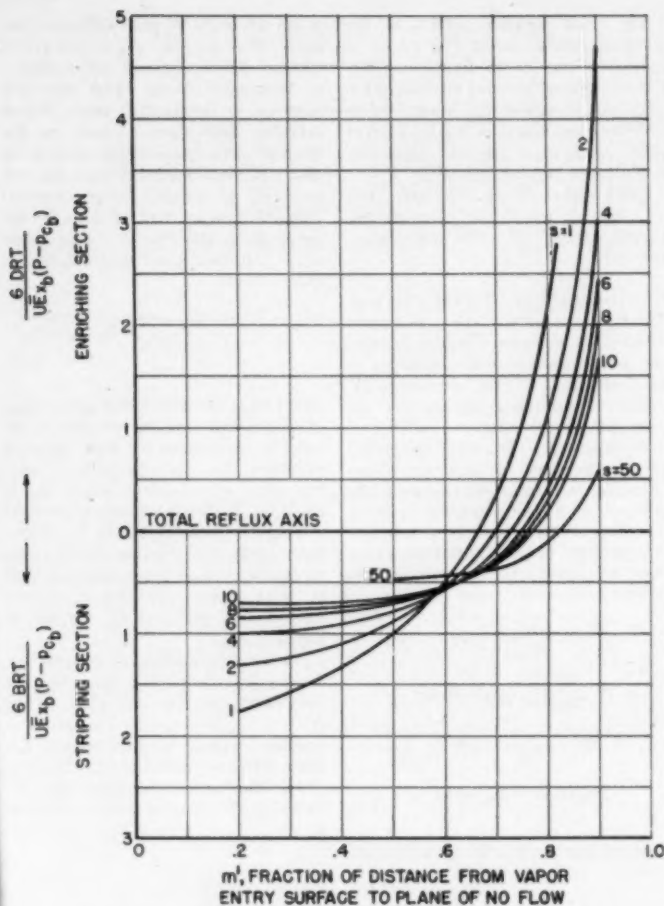
**Fig. 7.** Location of position of no flow in sweep diffusion working space. (Parallel plane case.)

In Equation (57), $\overline{p_0}$ and $(\overline{P - p_0})$ are evaluated in the usual manner by means of Equations (19) and (21). Comparison of equations (31) and (55) shows that inclusion of the thermal diffusion effect does not change the form of the transport equation.

*Solutions of the Transport Equations.* Equation (55) is a first-order, first-degree differential equation whose variables are separable in the following manner:

$$\frac{dy}{-ny_D + y(1-n) - y^2} = \frac{H}{K} dz$$

(58)

where

$$n = \frac{D}{H}$$

(59)

*Exact Solution.* Integration of Equation (58), satisfying the boundary conditions:

at $z = 0$, $y = y_F$
at $z = Z_s$, $y = y_D$

(60)

yields

$$\tanh \frac{b'HZ_s}{2K} = \frac{b'(y_D - y_F)}{y_D + y_F - n(y_D - y_F) - 2y_Dy_F}$$

(61)

where

$$b' = [(1+n)^2 - 4ny_D]^{\frac{1}{2}}$$
$$= [(1-n)^2 + 4n(1-y_D)]^{\frac{1}{2}}$$

(62)

Equations (61) and (62) combined with previous equations for the process constants enable calculation of the product purity, $y_D$ for a given product

rate, $D$, and feed composition, $y_F$, in a sweep diffusion column of given dimensions having certain values for the process parameters $H$ and $K$. They may be used also for calculating the product rate possible for a given product purity, or the length of column required for a given product rate and purity. Since trial-and-error solution is required for calculating product purity or product rate from Equations (61) and (62) several special solutions (6) are given.

*Solution for $0.3 < y < 0.7$.* When $y$ lies in the range 0.3 to 0.7 throughout the column, $y(1-y)$ is practically constant at 0.25 and Equation (58) has the simpler solution

$$y_D = y_F + \frac{1 - e^{-DZ_s/K}}{4n}$$

(63)

*Solution for $y \ll 1$*

$$y_D = \frac{y_F(1+n)}{e^{-Z_s(H+D)/K} + n}$$

(64)

*Solution for $(1-y) \ll 1$*

$$y_D = 1 - \frac{(1 - y_F)(1-n)}{e^{Z_s(H-D)/K} - n}$$

(65)

Equations (63), (64), and (65) are quite convenient for the range in which they hold in that they enable direct solution for $y_D$ without trial and error.

*Solution for Total Reflux.* At total reflux, where $D$ is zero, Equation (58) integrates to

$$\frac{y_D(1 - y_F)}{y_F(1 - y_D)} = e^{HZ_s/K}$$

(66)

*Consideration of the Stripping Section.* Below the feed point the treatment is similar to that in the region of the column above the feed point. Thus the transport Equation (16) becomes

$$By_B = V(y^{II} - y^I) + By + \tau_{1,6}$$

(16s)

Equations (17)-(19) remain unchanged. In Equation (20), $\bar{y}$ is taken as the average composition in the stripping section. In Equations (21)-(27) no changes are necessary. Equation (28) is rewritten as follows:

$$-N_1Edz = V \frac{\partial y^I}{\partial z} dz$$

(28s)

which reduces to

$$N_1 = -\frac{V}{E} \frac{\partial y}{\partial z}$$

(29s)

In Equations (30), (32)-(33), $L$ is replaced by $V$. The value for $V$ in the stripper is calculated from the value obtained for $L$ from Equation (40) and the relationship,

$$V = L - B$$

(67)

Equations (31) and (53) are rewritten with $-B$ replacing $D$, and $y_B$ replacing $y_D$. Equations (34)-(45), (48), (50)-(52), (54), and (56) remain unchanged. In Equations (46), (47), and (49), $-B$ replaces $D$. Equation (55) is rewritten as follows:

$$By_B = -Hy(1-y) + By + K\frac{\partial y}{\partial z}$$

$$(55s)$$

In Equation (57), $L$ is replaced by $V$, and in Equation (58), $n$ is replaced by $-n$, and $y_D$ by $y_B$. Thus (58) and (59) become

$$\frac{dy}{ny_B + y(1-n) - y^2} = \frac{H}{K}\,dz$$

$$(58s)$$

where

$$n = \frac{B}{H}$$

$$(59s)$$

The new boundary conditions are:

at $z = 0$, $y = y_F$
at $z = -Z_s$, $y = y_B$   $(60s)$

The various solutions for the transport equation as applied to the stripping section are the same as for the enriching section with the following changes: $-n$ replaces $n$, $y_B$ replaces $y_D$, $-B$ replaces $D$, and $-Z_s$ replaces $Z_e$, keeping in mind the new definitions for the quantities $n$, $H$, and $K$ just discussed.

The solutions for the various cases which have already been treated for the enricher are presented below:

*Exact Solution*

$$\tanh\frac{b'HZ_e}{2K} = \frac{b'(y_F - y_B)}{y_B + y_F - n(y_F - y_B) - 2y_B y_F}$$

$$(61s)$$

$$b' = [(1-n)^2 + 4ny_B]^{\frac{1}{2}}$$
$$= [(1+n)^2 - 4n(1-y_B)]^{\frac{1}{2}}$$

$$(62s)$$

*Solution for* $0.3 < y < 0.7$

$$y_B = y_F - \frac{1 - e^{-nz_e/K}}{4n}$$

$$(63s)$$

*Solution for* $y << 1$

$$y_B = \frac{y_F(1-n)}{e^{z_e(H-B)/K} - n}$$

$$(64s)$$

*Solution for* $(1-y) << 1$

$$y_B = 1 - \frac{(1-y_F)(1+n)}{n + e^{-z_e(H+B)/K}}$$

$$(65s)$$

*Solution for Total Reflux*

$$\frac{y_B(1-y_F)}{y_F(1-y_B)} = e^{-nz_e/K}$$

$$(66s)$$

*Evaluation of* $y_F$. Study of transport Equations (16) and (16s) reveals that the term $y$ in Equation (16) is actually

$y^I$ while in Equation (16s) it is $y^{II}$. This means that in the solutions of Equation (16), the term $y_F$ refers more properly to $y_F{}^I$, the composition of the upflowing stream at the feed point while in the solutions of Equation (16s), $y_F$ refers to $y_F{}^{II}$, the composition of the downflowing stream at the feed point. For difficultly separable materials, such as mixtures of isotopes, this distinction has no effect on the calculated results. For easier separations, such as hydrogen-hydrocarbon gas mixtures, it would normally be necessary to observe this distinction. For example, if the feed is introduced into the upflowing stream, the $y_F$ in Equations (61s)-(66s) is set equal to the composition of the feed gas, since for proper design this composition should equal the composition of the stream with which it is being mixed. The value of $y_F$ to be substituted into Equations (61s) to (66s) is then calculated by a material balance on the enricher, as follows:

$$y_F{}^{II} = y_F{}^I - \frac{D}{L}(y_D - y_F{}^I)$$

$$(67s)$$

*Corrections for Annular Working Spaces.* The equations developed above apply strictly to separating zones bounded by parallel plane vapor entry and condensing surfaces. Corrections that should be made for concentric cylinder vapor entry and condensing surfaces are of interest because this arrangement has certain design advantages. The curvature of the central member is never as extreme as that of the hot wire thermal diffusion column, for in sweep diffusion the central member must serve either as a tube for vapor entry or as a surface on which vapor may condense. Thus, the recommended corrections due to curvature are of a gross nature and do not take into consideration the change in vapor flow rate per unit area in the $x$-direction.

The vapor flow rate per unit area, $N_0$, is calculated on the basis of the arithmetic average area of the vapor entry and condensing surfaces. The column width, $\overline{E}$, in Equations (23), (30), and (33) is taken as the arithmetic average circumference of the vapor entry and condensing surfaces.

The principal effect of curvature of the vapor entry and condensing surfaces appears in the evaluation of $m$ and $L$. Thus, Figure 7 applies strictly to the parallel plane case. For annular working spaces, it is recommended that $\overline{E}$ be taken as the arithmetic average circumference to evaluate the ordinate of Figure 7. The $m'$ obtained is the ratio of cross-sectional area of the upflowing to the downflowing stream, if the working space were not curved. To correct for

curvature, an $m$ is calculated which gives the same ratio of these areas for a space bounded by vapor entry and condensing cylinders of diameters $D_a$ and $D_b$, respectively. The resulting equation is:

$$m = \left|\frac{[(1-m')D_a{}^2 + m'D_b{}^2]^{\frac{1}{2}} - D_a}{2x_b}\right|$$

$$(68)$$

where use of the absolute, or positive, value permits application of this equation to cases where $D_a$ is greater or less than $D_b$. Equation (68) applies to either the stripping section or the enriching section. The value of $m$ obtained from Equation (68) is used in Equation (40).

The other correction for curvature is in the value of $E^{II}$ used in Equation (40). For the parallel plane case, $E^{II} = \overline{E} = E_a = E_b$. For curved surfaces, $E^{II}$ is taken as the circumference at a central point in the downflowing stream. A good approximation is the midpoint position $x = x_b(1 + m)/2$. Thus, if $E_b > E_a$,

$$E^{II} = E_b - \pi x_b(1-m)$$   $(69)$

and if $E_b < E_a$,

$$E^{II} = E_b + \pi x_b(1-m)$$   $(70)$

*Distillation Analogy.* There is a formal mathematical analogy between the theories of sweep diffusion and of distillation. By proper choice of the parameters, the equations of performance in sweep diffusion are the same as in distillation.

As is demonstrated later, the thermal diffusion effect $(H_F)$ is generally small in a properly designed sweep diffusion column, and for simplicity, it will be assumed negligible in this section.

The separation factor, $\alpha$, for the column process is herein defined as follows:

$$\alpha = \frac{y^I(1-y^{II})}{y^{II}(1-y^I)} = \frac{(p_1{}^I)(p_2{}^{II})}{(p_1{}^{II})(p_2{}^I)}$$

$$(71)$$

under conditions of no diffusion of components 1 or 2 along $x$ and no convection along $z$. Since the average stream compositions, $y^I$ and $y^{II}$ are located at points approximately $0.5x_b$ cm. apart, integration of Equation (4) and its counterpart in $p_2$ yields

$$\frac{p_1{}^I}{p_1{}^{II}} = e^{\frac{-0.5x_b N_0 RT}{D_m P}}$$

$$(72)$$

and

$$\frac{p_2{}^I}{p_2{}^{II}} = e^{\frac{-0.5x_b N_0 RT}{D_m P}}$$

$$(73)$$

so that

$$a = e^{\frac{0.5 \sigma_1 N_0 RT}{P}\left(\frac{1}{D_{01}} - \frac{1}{D_{02}}\right)}$$

(74)

Combining Equations (74) and (32) affords

$$a = e^{H_s/L}, \text{ or, } \frac{H_s}{L} = \ln a$$

(75)

For operation at total reflux, the Fenske (8) equation yields

$$a^{Z_s/H_t} = \frac{y_D(1 - y_F)}{y_F(1 - y_D)}$$

(76)

where $H_t$ is the height equivalent to a theoretical plate.

Combining Equations (66) and (76), one obtains

$$\frac{\ln a}{H_t} = \frac{H}{K}$$

(77)

Since thermal diffusion is neglected, $H = H_s$. Combining Equations (77) and (75),

$$H_t = \frac{K}{L}$$

(78)

For the stripping section, $L$ is replaced by $V$ in Equations (75) and (78).

The transport equation may be written in terms of $a$ and $H_t$ by combining Equations (75) and (78) with Equation (55) to yield

$$H_t \frac{dy}{dz}$$

$$= (\ln a)y(1 - y) - \frac{D}{L}(y_D - y)$$

(79)

For the stripping section,

$$H_t \frac{dy}{dz}$$

$$= (\ln a)y(1 - y) - \frac{B}{V}(y - y_B)$$

(79s)

where in equation (79s) $H_t = K/V$ and $\ln a = H_s/V$.

A material balance on the column yields, for the composition change across any theoretical plate in the enricher,

$$\Delta y = \frac{(a - 1)y(1 - y)}{a - y(a - 1)} - \frac{D}{L}(y_D - y)$$

(80)

The coefficient of $y(1 - y)$ in Equation (80) has a maximum value of $(a - 1)$ when $y = 1$ and a minimum value of $(a - 1)/a$ when $y = 0$. These values lie on opposite sides of the value for $\ln a$ appearing in Equation (79) and approach each other as $a$ approaches

one. Under conditions where $a$ is close to unity, comparison of (79) and (80) reveals that $H_t dy/dz$ approaches $\Delta y$, or

$$\text{Limit}_{a \to 1} \quad H_t = \frac{\Delta y}{dy/dz}$$

(81)

This states that the slope of the composition vs. height curve equals the increment in y divided by the increment in $z$ when the enrichment per theoretical plate is small, i.e., when $a$ is nearly one.

Equation (80) may be solved by the McCabe-Thiele graphical method (10) used in distillation. Thus, for any $a$, $D$, $L$, $y_F$ and $y_D$, the number of theoretical plates required may be stepped off in the usual manner. When $a$ is close to unity, the height of column required may be obtained by multiplying the number of theoretical plates obtained by graphical solution by the height equivalent to a theoretical plate. However for large values of $a$, $H_t$ is no longer equal to $\Delta y$ divided by $dy/dz$, and it is necessary to utilize the accurate solutions to the differential equation as presented in Equations (61)-(66).

*Treatment of Multiple Surface Units.* In an apparatus employing a number of surfaces connected in parallel, such as tubes mounted in tube sheets, no change in the equations is required. The values of $L$, $V$, $E$, $F$, $D$, and $B$, however, must represent summations of each of these quantities for all the tubes.

### The Tapered Plant

The preceding section on the column process applies principally to single section, "untapered" units. In such units there may be numerous tubes in parallel, but the total gas reflux rate at any position along the unit is constant. In a tapered unit, the gas reflux rate is smaller near the product ends of the unit. This would normally be effected by reducing the number of tubes in parallel as the product ends of the plant are approached. Sweep diffusion plants of untapered design are applicable mainly to the rough separation of easily separable materials. Where sharp separations are desired, or where the materials to be separated are difficultly separable, the untapered plant is wasteful of power and has a long start-up time.

In the development that follows, the effect of thermal diffusion and longitudinal diffusion are assumed to be negligible. Besides this, $f_L$, which equals $L/E$, is assumed constant at all points along the enricher, and $f_V$, equal to $V/E$, is assumed constant at all points along the stripper. This means that variation in $L$ or $V$ with $z$ is achieved by varying $E$, which may be done by changing the

number of identically operating tubes connected in parallel at different points along the length of the plant.

*Optimum Reflux Rate for Minimum Surface.* The total vapor entry surface in the enriching section of a sweep diffusion unit is given by

$$A_e = \int_0^{Z_e} E dz$$

(82)

where $E$ is permitted to vary with $z$ in some manner. Combining Equation (82) and (79), the enriching section surface is given by

$$A_e =$$

$$\int_{y_F}^{y_D} \frac{H_t E dy}{(\ln a)y(1 - y) - \frac{D}{E f_L}(y_D - y)}$$

(83)

where $L$ has been replaced by $E f_L$. For a given $x_1$, $N_0$, $T$, $P$, $D_{01}$, $D_{02}$, and $D_{12}$, $a$ is a constant. Likewise, substituting Equation (33) into (78) reveals that the variation of $H_t$ with y is small, and hence for a given $D$ and $y_D$, the only variables under the integral sign in Equation (83) are $E$ and y. The function $E(y)$ which minimizes the surface required and therefore, also, the energy required (to generate vapor) is that function which makes the integral a minimum. This has been shown by Jones and Furry, and by Benedict, to be

$$E_{opt} = \frac{2D(y_D - y)}{f_L(\ln a)y(1 - y)}$$

(84)

where, in their equations, $a - 1$ appears in place of $\ln a$. Rewritten,

$$L_{opt} = \frac{2D(y_D - y)}{(\ln a)y(1 - y)}$$

(85)

so that the ideal plant is tapered in order to provide smaller and smaller reflux rates as the product end of the unit is reached.

By setting $dy/dz$ equal to zero in Equation (79), a minimum reflux rate can be calculated at any value of y, which is given by

$$L_{min} = \frac{D(y_D - y)}{(\ln a)y(1 - y)}$$

(86)

Comparing Equations (85) and (86) shows that for the ideal tapered plant, the optimum reflux rate is everywhere twice the minimum reflux rate. The same relation holds for the stripping section, where the reflux rate is defined as $V$. Thus,

$$E_{opt} = \frac{2B(y - y_B)}{f_V(\ln a)y(1 - y)}$$

(84s)

and

$$V_{opt} = 2V_{min} = \frac{2B(y - y_B)}{(ln\ a)y(1-y)}$$
(87)

*Calculation of Surface Required in Ideal Tapered Plant.* Substituting Equation (85) into (83), simplifying, and integrating, one obtains

$$A_e = \frac{4DH_t}{f_L(ln\ a)^2}\left[\frac{(1-2y_F)(y_D-y_F)}{y_F(1-y_F)} - (1-2y_D)ln\ \frac{y_D(1-y_F)}{y_F(1-y_D)}\right]$$
(88)

By similar arguments, in the stripping section

$$A_s = \frac{4BH_t}{f_V(ln\ a)^2}\left[\frac{(1-2y_F)(y_B-y_F)}{y_F(1-y_F)} + (1-2y_B)\ ln\ \frac{y_F(1-y_B)}{y_B(1-y_F)}\right]$$
(88s)

where for the stripper, $H_t = K_s/V$, $f_V = V/E$, and $ln\ a = H_B/V$.

*Evaluation of Total Surface Required.* In both the stripper and the enricher, $a$ is given by Equation (74), and since in the design under consideration, $N_0$ and the other quantities in Equation (74) are constant, the values of $a$ in Equations (88) and (88s) are identical. The equation for $H_t/f_L$ in the enricher is the same as that for $H_t/f_V$ in the stripper. The value in each case is given by

$$\frac{H_t}{f_L} = \frac{0.5x_bRT}{P}\left[\frac{1}{D_{12}} + \frac{\overline{p_0}}{P-\overline{p_0}}\left(\frac{\overline{1-y}}{D_{01}} + \frac{\overline{y}}{D_{02}}\right)\right]$$
(89)

The values of $\overline{p_0}$ and $\overline{y}$ are different for the stripper and the enricher, but in such a direction as to compensate somewhat for each other. For separations of components whose diffusivities are nearly equal, a single value of the quantity (89) is satisfactory for any assumed value of $\overline{y}$. For mixtures of dissimilar gases, the evaluation of (89) at $\overline{y} = (y_D + y_B)/2$ serves as a satisfactory average for both the enricher and the stripper for ordinary computation. Using a single value for $H_t/f_L$ in the enricher and stripper enables one to simplify the sum of Equations (88) and (88s) to obtain for the entire unit

$$A_t = A_e + A_s =$$

$$\frac{4H_t}{f_L(ln\ a)^2}\left[-D(1-2y_D)ln\ \frac{y_D(1-y_F)}{y_F(1-y_D)} + B(1-2y_B)ln\ \frac{y_F(1-y_B)}{y_B(1-y_F)}\right]$$
(90)

where $H_t/f_L$ is a mean value calculated at the arithmetic average of the top and bottom product compositions.

*Height of Ideal Tapered Plant.* By combining Equations (79) and (85), it is readily shown that for the ideal tapered plant

$$\frac{dy}{dz} = \frac{(ln\ a)y(1-y)}{2H_t}$$
(91)

which is one-half the concentration gradient for operation at total reflux

($D = 0$) for the same values of $a$ and $H_t$. Thus the total height of the plant $Z_t$ is twice the height required to perform the separation at total reflux. The height at total reflux, $Z_{min}$, is obtained by dividing Equation (66) by (66s) to yield

$$e^{\frac{H_B Z_{min}}{K_s}} = \frac{(y_D)(1-y_B)}{(y_B)(1-y_D)}$$
(92)

Thus, for the ideal tapered plant, the total height is given by

$$Z_t = 2Z_{min} = \frac{2H_t}{ln\ a}ln\ \frac{y_D(1-y_B)}{y_B(1-y_D)}$$
(93)

Likewise, at any elevation in the enricher above the feed point,

$$Z_e = \frac{2H_t}{ln\ a}ln\ \frac{y(1-y_F)}{y_F(1-y)}$$
(94)

and in the stripper,

$$Z_s = \frac{-2H_t}{ln\ a}ln\ \frac{y_F(1-y)}{y(1-y_F)}$$
(94s)

*Minimum Vapor Requirements and Minimum Total Area for Ideal Tapered Plant.* The total vapor consumption rate in the ideal tapered plant is equal to the product $N_0A_t$, where $A_t$ is given by Equation (90). If one is considering performing a certain separation, the quantity in the brackets is fixed, and the total vapor rate is proportional to $N_0H_t/f_L(ln\ a)^2$. From Equations (74) and (89), one obtains for this quantity

$$\Phi = \frac{N_0H_t}{f_L(ln\ a)^2} = $$

$$\frac{\frac{1}{D_{12}} + \frac{\overline{p_0}}{P-\overline{p_0}}\left(\frac{\overline{1-y}}{D_{01}} + \frac{\overline{y}}{D_{02}}\right)}{\frac{0.5x_bN_0RT}{P}\left(\frac{1}{D_{02}} - \frac{1}{D_{01}}\right)^2}$$
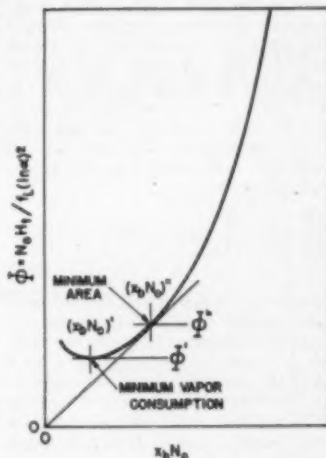(95)



Fig. 8. $\phi$ vs. $x_bN_0$ for ideal tapered plant.

Restricting Equation (95) to the consideration of the separation of a certain binary gas mixture with a certain sweep vapor, operating under known conditions of temperature and pressure, it is noted that the only variables remaining in Equation (95) are $x_b$, $N_0$, and $\overline{p_0}$. Inspection of Equations (19)-(21) shows that $\overline{p_0}$ is a function of the product $x_bN_0$. Returning to Equation (95), it is obvious that the total vapor rate required to perform a certain separation in an ideal tapered plant is a unique function of the quantity $x_bN_0$. At different assumed values of $x_bN_0$, values of the quantity $\Phi$ may be determined, and a curve may be plotted as shown in Figure 8. The minimum vapor consumption occurs at the point, $[(x_bN_0)', \Phi']$, where the curve goes through a minimum.

It is desirable to know also at what values of $x_b$, and $N_0$ the total area required is a minimum. From Equations (90) and (95), $A_t$, the area required, is proportional to $\Phi/N_0$. For any diffusional distance, $x_b$, it is possible to evaluate the conditions for minimum total area by taking the first derivative of $\Phi/N_0$ with respect to $N_0$, and setting it equal to zero. Proceeding from the relation that $\Phi$ is a function of $x_bN_0$, one obtains, at minimum area,

$$\frac{\partial \Phi}{\partial N_0} = \frac{\Phi}{N_0}$$
(96)

Since $x_b$ is being held constant, Equation (96) may be rewritten:

$$\frac{\partial \Phi}{\partial (x_bN_0)} = \frac{\Phi}{x_bN_0}$$
(97)

Referring back to Figure 8, it is apparent that the conditions for minimum

area in the ideal tapered plant correspond to the point at which a straight line going through the origin is tangent to the curve. This point is designated by the coordinates $[(x_b N_0)'', \Phi'']$. The $x_b N_0$ for minimum area is obviously not the same as the $x_b N_0$ for minimum vapor consumption. The area required under the conditions of minimum area is proportional to

$$\frac{\Phi''}{N_0} = \left[ \frac{\Phi''}{(x_b N_0)''} \right] (x_b) = (const.)(x_b) \quad (98)$$

so that it is apparent that the minimum area required is proportional to the diffusional distance $x_b$. Lowering the value of $x_b$ reduces the area required without affecting the total vapor consumption, provided that $N_0$ is permitted to increase in inverse proportion to $x_b$ so as to keep their product constant. Practical design considerations will place a lower limit on the value of $x_b$ that can be used. Economic factors will determine whether to operate under conditions closer to $(x_b N_0)'$, where the vapor consumption is a minimum, or closer to $(x_b N_0)''$, where the area is a minimum.

*Choice of $f_L$ or $f_V$.* It is apparent from Equation (95) that neither the vapor rate nor the area of vapor entry surface required is affected by the choice of $f_L$ or $f_V$ in ideal tapered plants. However, there is an upper limit on the value of these quantities above which eddies in the separating zone become appreciable. Variation below this limiting value changes the width and height of the plant in opposite directions. Thus large values for $f_L$ and $f_V$ result in long, narrow plants while small values result in short wide plants.

## Notation

$A$ = area of vapor entry surface, sq.cm.

$B$ = bottom product rate, g. moles/sec.

$D$ = diameter of tube, cm.

$D$ = top product rate, g.moles/ sec.

$D_{12}, D_{02},$
$D_{01}$ = diffusivity, sq.cm./sec.

$\epsilon$ = base of natural logarithms

$E$ = width of column perpendicular to $x$ direction, cm.

$f$ = Fanning friction factor

$f_L = L/E$

$f_V = V/E$

$F$ = feed rate, g. moles/sec.

$g$ = gravitational constant, 980 cm./(sec.)(sec.)

$H = H_s + H_T$ (g.moles)/sec.

$H_s$ = transport coefficient for sweep diffusion, g.moles/ sec.

$H_T$ = transport coefficient for thermal diffusion, g. moles/sec.

$H_t$ = height equivalent to a theoretical plate, cm.

$\Delta h$ = enthalpy change of vapor, cal./g.mole

$K = K_c + K_d$

$K_c$ = coefficient for convection term in sweep diffusion, (cm.)(g.moles)/sec.

$K_d$ = coefficient for longitudinal diffusion term in sweep diffusion, (cm.) (g. moles)/sec.

$l$ = thickness of liquid curtain, cm.

$L$ = downflow rate of vapor-free gas, g.moles/sec.

$m$ = fraction of distance from vapor entry surface to point of no vertical flow

$M$ = molecular weight

$N$ = rate of diffusion, g.moles/ (sq.cm.)(sec.)

$n = D/H$

$p_1, p_2,$
$p_0$ = partial pressure of one component of gas-vapor mixture, atm.

$P$ = total pressure, atm.

$R$ = gas constant, 82.06 (cc.) (atms.)/(g. mole)(° K.)

$Re_l$ = Reynolds number of liquid

$Re_g$ = Reynolds number of gas

$R_T$ = ratio of actual value of thermal diffusion constant to value it would have for hard spherical molecules

$S.C.F.H.$ = standard cubic feet per hr. measured at 32° F. and 1 atm.

$s$ = defined by Eq. (20)

$T$ = abs. $T$., ° K.

$U$ = gas velocity at the gas-liquid interface, cm./sec.

$v_l$ = average liquid velocity, cm./sec.

$V$ = upflow rate of vapor-free gas, g.moles/sec.

$V_1, V_2,$
$V_0$ = molecular volume

$w$ = flow rate of liquid curtain, g./sec.

$x$ = distance from vapor entry surface, cm.

$y, y_0,$
$y_a, y_b,$
$y^I, y^{II},$
$y_B, y_D, y_F$ = mole fraction of more diffusible component of gas on a vapor-free basis

$y_1, y_2, y_0$ = mole fraction of components 1, 2, and 0, respectively, on a total gas-plus-vapor basis

$z$ = vertical distance, cm.

$Z$ = length of column between feed point and product withdrawal point, cm.

GREEK LETTERS:

$\alpha^\circ$ = sweep diffusion single-stage point separation factor

$\alpha$ = separation factor for sweep diffusion column process

$\alpha^*$ = thermal diffusion constant

$\epsilon$ = column efficiency

$\Phi$ = defined by Eq. (95)

$\mu$ = viscosity, poises

$\rho$ = density, g./cu.cm.

$\tau_{1d}$ = diffusion of more diffusible component down column, g.moles/sec.

SUPERSCRIPTS:

$\circ$ = conditions of no gas convection in $z$ direction and no diffusion of gas (1 or 2) in $x$ direction

$I$ = average conditions in upflowing stream

$II$ = average conditions in downflowing stream

—— = a bar above a letter, refers to a mean value

SUBSCRIPT REFERS TO:

$_0$ = vapor

$_1$ = more diffusible gas component

$_2$ = less diffusible gas component

$_a$ = vapor entry wall

$_b$ = vapor-condensing wall

$_B$ = bottom product

$_c$ = convection

$_D$ = top product

$_d$ = diffusion

$_e$ = enriching section

$_F$ = feed gas or feed location

$_g$ = gas

$_l$ = liquid

$_s$ = sweep diffusion

$_s$ = stripping section

$_T$ = thermal diffusion

*The remainder of this article, presenting experimental data and discussing the application of sweep diffusion to the separation of isotopes and the purification of hydrogen, will appear in following issues of Chemical Engineering Progress.*

# LIQUID METAL HEAT-TRANSFER COEFFICIENTS[†]

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INTEREST in the use of liquid metals as heat-transfer media has grown because of their high boiling point and their resistance to thermal decomposition. Qualitatively it has also been recognized that the heat-transfer coefficients with liquid metals are higher than with any other fluid for a given system and pumping power. However, the few experimental data presented in the literature have shown that liquid metal heat-transfer coefficients cannot be predicted with assurance by the standard equation for ordinary fluids.

Such expressions as the Colburn and Dittus-Boelter equations have been developed empirically over a Prandtl modulus range of less than two and a half orders of magnitude beginning only slightly below a Prandtl modulus of one. Liquid metals may have Prandtl moduli as low as .005, or almost two and a half orders of magnitude below the range used in developing the usual relationships. As a result there is no justification in believing that these expressions will apply for liquid metals.

The current concept of turbulent flow in a tube is shown qualitatively in Figure 1. A thin laminar or viscous region in which no turbulence or eddying takes place occurs adjacent to wall. All conduction of heat and momentum is by molecular motion (and by electron motion in the case of liquid metals).

Between this layer and the turbulent core is a buffer region in which the velocity distribution is determined by the combined action of molecular and eddy diffusion of momentum toward the wall. In the turbulent core the velocity distribution, by definition, is controlled by the eddy diffusion of momentum.

Numerical comparison of the conductivity of heat with conductivity of momentum or viscosity can be accomplished by converting to units of dif-

fusivity, (length)$^2$ per time. Thermal conductivity divided by the volume heat capacity represents thermal diffusivity; and kinematic viscosity, or absolute viscosity divided by density, represents the diffusivity of momentum.

The ratio of molecular diffusivity of momentum to molecular diffusivity of heat for a given fluid is represented by the Prandtl modulus:

$$Pr = \frac{c\rho}{k} \cdot \frac{\mu}{\rho} = \frac{c\mu}{k} \qquad (1)$$

The corresponding ratio for eddy diffusivities, following the example of Martinelli (7), will be assumed to be a constant, $1/a$; thus

$$\epsilon_H = a\epsilon_M \qquad (2)$$

In the bulk of the following discussion, $a$ will be assumed to be unity, and most heat-transfer evidence leads to this conclusion. In view of some uncertainty on this point, however, $a$ will be carried through the general mathematical development which follows.



Fig. 1. Qualitative diagram of temperature distribution in fluids of various Prandtl moduli.

Again referring to Figure 1, the curve marked "$Pr = 1$" may be thought of as picturing qualitatively the temperature distribution in a cooling tube under given conditions where the fluid has a Prandtl modulus of unity. Such a situation is approximated by a gas and by high temperature water. It also represents the shape of the velocity distribution, although, of course, inverted.

The upper curve represents the temperature distribution for most liquids where the Prandtl modulus is greater than one—poor molecular diffusivity of heat compared with momentum. Here the temperature distribution curve deviates from the velocity distribution curve in the buffer region, because of the low influence of molecular diffusivity of heat.

The temperature distribution curve for liquid metals or other fluids with high molecular diffusivity of heat and hence Prandtl modulus less than unity is represented by the lowest curve. In this case the effect of high molecular diffusivity (and electron diffusivity) of heat will be pronounced even in the turbulent core. For low Prandtl modulus at moderate Reynolds modulus, the eddying may not control completely heat flow even near the center of the tube.

Reynolds (12), in his derivation, assumed that turbulence extended to the wall and that $a$ was unity. On this basis he did not require a knowledge of the actual velocity distribution. Relating fluid friction to heat transfer, he obtained

$$Nu = \frac{f}{2} Re \cdot Pr \qquad (3)$$

Using a rough empirical equation (6) for the friction factor, $f$, this may be written

$$Nu = \frac{.046 \, Re^{-.2}}{2} Re \cdot Pr$$

$$= .023 \, Re^{.8} \cdot Pr \qquad (4)$$

[†] This work was carried out at Oak Ridge National Laboratory which is operated by Carbide and Carbon Chemicals Corp. for the Atomic Energy Commission under Contract No. W-7405, eng. 26.

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## CONTROL PANEL FOR NaK HEAT-TRANSFER SYSTEM
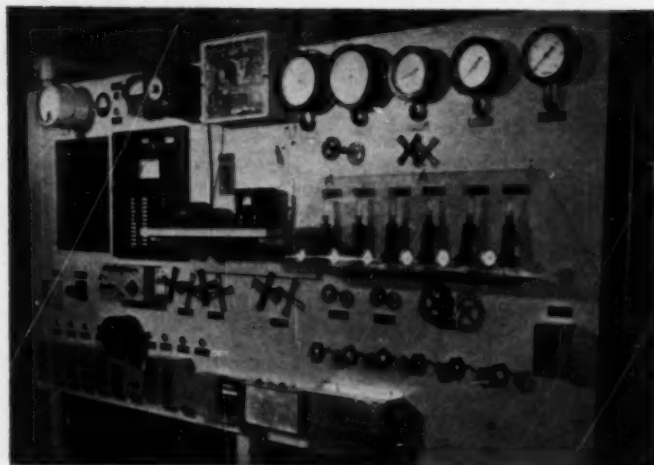
Shows heater controls; multipoint temperature indicator; indicator and amplifier for electromagnetic flowmeter; catch tank probe relay system and timer; sump tank level indicator; protective gas pressure indicator and controller; system flow control valves; cooling oil controls for packing glands, and evaporator-cooler control valves.

### VIEW FROM LEFT OF PANEL
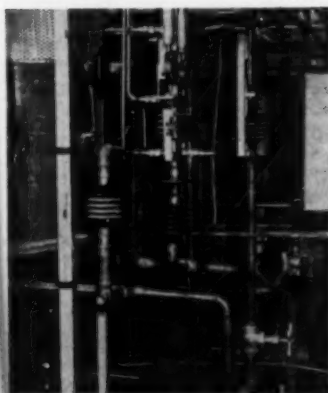
Shows lower end of heating tank, and one of test heat exchangers; also dial gages used in an unsuccessful attempt to measure the temperature of the inner tube by its linear expansion. Top of the sump tank with the pump motor can be seen in the background.

As long as the heat and momentum diffusivities are equal, this equation should apply, and experiences with gases bears out such a prediction.

The well-known Dittus and Boelter equation and the Colburn equation in effect add an empirical correction to the Reynolds equation to account for the deviation of the temperature distribution from the velocity distribution in the buffer and laminar regions.

The Colburn (2) expression may be written:

$$Nu = .023 \ Re^{.8}Pr \ \ Pr^{-\%}$$
$$= .023 \ Re^{.8}Pr^{\frac{1}{4}} \qquad (5)$$

It is obvious that a different correction may be required in the case where the divergence of temperature distribution from velocity distribution occurs in the turbulent core, and such appears to be the case.

Prandtl (10) and Taylor (14) developed improvements on the Reynolds analysis by assuming a laminar region close to the wall. Karman (4) added the effect of a buffer region in his analysis. Boelter, Martinelli and Jonassen (1), and Reichardt (11) have suggested variations to account for the change in viscosity due to radial temperature gradients near the wall.

Martinelli (7) first introduced the effect of molecular diffusivity in the turbulent core. While the hypothetical system studied in this paper is similar, and the analysis is parallel with that of Martinelli as well as that of Karman (4), it is believed that the development here is more suitable to chemical engineers and that the final results are much more usable.

*A General Equation for the Heat-Transfer Coefficient in Tubes.* The tube-fluid system studied in this section is defined by the following specifications:

1. Steady state
2. Constant physical properties of fluid
3. No end effects
4. System symmetrical about tube axis
5. Constant heat flux along the tube wall (in the $Z$ direction)

Under these conditions, the temperature at a given distance from the center of the tube will increase linearly along the tube, while other properties will vary only with the distance from the center of the tube. The increase in temperature with tube length at constant distance from the tube center, $\partial T/\partial Z$, will be independent of distance along the tube and distance from the center of the tube.

By definition

$$h = \frac{q_w}{A_w(t_w - t_m)} \qquad (6)$$

If a unit length of tube is considered, a heat balance gives:

$$q_w = \pi r_w^2 c\rho u_m \frac{\partial t}{\partial Z} \qquad (7)$$

In this unit length,

$$A_w = 2\pi r_w \qquad (8)$$

If the heat $q$ is thought of as flowing toward the center of the tube, the bulk temperature is defined by the equation

$$t_m = \frac{\int_0^{r_w} r_t u_t t dr_t}{\int_0^{r_w} r_t u_t dr_t}$$
$$= 2\frac{\int_0^{r_w} r_t u_t t dr_t}{r_w^2 u_m} \qquad (9)$$

Hence,

$$t_w - t_m = (t_w - t)_m$$
$$= 2\frac{\int_0^{r_w} r_t u_t (t_w - t) dr_t}{r_w^2 u_m} \qquad (10)$$

If $K$ is the sum of the molecular conductivity, $k$ and the eddy conductivity, $E$,

$$(t_w - t) = \int_{r_t}^{r_w} \frac{\partial t}{\partial r} \ dr$$
$$= \int_{r_t}^{r_w} \frac{q}{2\pi r_q K} dr_q \qquad (11)$$

By a heat balance around a cylinder of unit length and radius $r_q$ in the fluid,

$$q = \int_0^{r_q} 2\pi r u c_p \frac{\partial t}{\partial z} \, dr$$

$$(12)$$

Substitution of Equation (12) into Equation (11), Equation (11) into Equation (10) and Equations (10), (8), and (7), into Equation (6), will give the following equation for $h$, the heat-transfer coefficient, upon appropriate rearrangement:

$$h = \frac{r_w{}^3 u_m{}^2}{4 \int_0^{r_w} r_t u_t \left[ \int_{r_t}^{r_w} \frac{\int_0^{r_q} r u \, dr}{r_q K} \, dr_q \right] dr_t}$$

If the relative velocity, $V$, is defined by

$$V = \frac{u}{u_m} \qquad (14a)$$

and the relative distance to the wall by

$$S = \frac{r}{r_w} \qquad (14b)$$

then,

$$\frac{1}{h} = 4 r_w \int_0^1 \int_{S_t}^1 \int_0^{S_q} \frac{S_t V_t S V}{S_q K} \, dS_t \, dS_q \, dS \qquad (15)$$

Since,

$$Nu = \frac{2 h r_w}{k} \qquad (16)$$

it can be shown, by changing the order of integration, that Equation (15) leads to the expression

$$\frac{1}{Nu} = 2 \int_0^1 \frac{\left[ \int_0^{S_q} V S \, dS \right]^2}{S_q \frac{K}{k}} \, dS_q \qquad (17)$$

The ratio of total to molecular conductivity of heat may be written:

$$\frac{K}{k} = \left( 1 + a Pr \frac{\epsilon_M}{\nu} \right) \qquad (18)$$

and when substituted into Equation (17) the result is:

$$\frac{1}{Nu} = 2 \int_0^1 \frac{\left[ \int_0^{S_q} V S \, dS \right]^2}{S_q \left( 1 + a Pr \frac{\epsilon_M}{\nu} \right)} \, dS_q \qquad (19)$$

Equations (17) and (19) represent general expressions by which the heat-transfer coefficient can be calculated in the system under discussion regardless of the flow regime which exists—viscous flow, turbulent flow or slug flow.

The heat-transfer coefficient under two specific situations may be computed

directly from Equation (17) or Equation (19). The first of these is the case of viscous flow, where no eddying occurs and where the velocity distribution is a paraboloid. Under this condition:

$$V_{visc} = 2 - 2S^2 \qquad (20)$$

The resulting solution is:

$$Nu_{visc} = \frac{48}{11} = 4.36 \qquad (21)$$

Another case of interest is that of slug flow under conditions in which the molecular diffusivity of heat controls to the center of the tube. Here $V$ is unity throughout the system, and the result is:

$$Nu = 8 \qquad (22)$$

From these results, one would expect the minimum value of $Nu$ for turbulent flow, as $Pr$ becomes very small, to be between 4.36 and 8. It is found to be approximately 7.0.

Numerical solutions of general Equation (19) for a range of $Pr = 0$ to $Pr = .1$ and of $Re = 4000$ to $Re = 3,240,000$ were made using the actual smoothed data of Nikuradse (9) for velocity distribution in tubes. These did not differ materially from results of Martinelli (7) who, in his parallel analysis, used the Karman-Nikuradse equations for velocity distribution.

Both sets of calculated results can be represented with reasonable accuracy by a new simple approximate equation:

$$Nu = 7 + .025 \, Pe^{.8}\dagger \qquad (23)$$

$Pe$ represents the Peclet modulus, $Du_m \rho c / k$ and may be easily found by

---

† If $a$ is assumed not to be unity, Equation (23) becomes:

$$Nu = 7 + .025 (a Pe)^{.8}$$

TABLE 1

COMPARISON OF NUSSELT MODULUS OBTAINED
EQUATIONS (19) AND (23)

| Re | Pr | Pe | Nu, using Equation (19) | Nu, using Approximate Equation (23) |
|---|---|---|---|---|
| $4 \times 10^3$ | 0 | 0 | 6.75 | 7.0 |
| | $10^{-3}$ | 4 | 6.76 | 7.08 |
| | $10^{-2}$ | 40 | 7.41 | 7.47 |
| | $10^{-1}$ | 400 | 11.03 | 10.0 |
| $4.34 \times 10^4$ | 0 | 0 | 6.83 | 7.0 |
| | $10^{-3}$ | 43.4 | 7.30 | 7.51 |
| | $10^{-2}$ | 434 | 10.30 | 10.2 |
| | $10^{-1}$ | 4,340 | 30.5 | 27.3 |
| $3.96 \times 10^5$ | 0 | 0 | 7.05 | 7.0 |
| | $10^{-3}$ | 396 | 9.54 | 9.83 |
| | $10^{-2}$ | 3,960 | 26.5 | 25.90 |
| | $10^{-1}$ | 39,600 | 136. | 127 |
| $3.24 \times 10^6$ | 0 | 0 | 7.17 | 7.0 |
| | $10^{-3}$ | 3,240 | 20.8 | 21.6 |
| | $10^{-2}$ | 32,400 | 100. | 106. |
| | $10^{-1}$ | 324,000 | 613. | 633. |

TABLE 2

COMPARISON OF EQUATION (23) WITH RESULTS OF
MARTINELLI FOR TUBES

| Pe | Values of Nu According to Martinelli | | | | Nu using Approximate Equation (23) |
|---|---|---|---|---|---|
| | $Pr = 10^{-4}$ | $Pr = 10^{-3}$ | $Pr = 10^{-2}$ | $Pr = 10^{-1}$ | |
| 10 | 7.29 | 7.08 | | | 7.16 |
| 100 | 8.11 | 8.06 | 7.97 | | 8.00 |
| 1,000 | 12.5 | 13.3 | 14.5 | 14.00 | 13.28 |
| 10,000 | | 43.3 | 48.7 | 53.00 | 46.6 |
| 100,000 | | | 244 | 271 | 257 |
| $10^6$ | | | 1649 | 1580 | |

NOTE: These values were obtained from a correction leaflet published by Dr. Martinelli and containing recalculated values of the results listed in his paper.
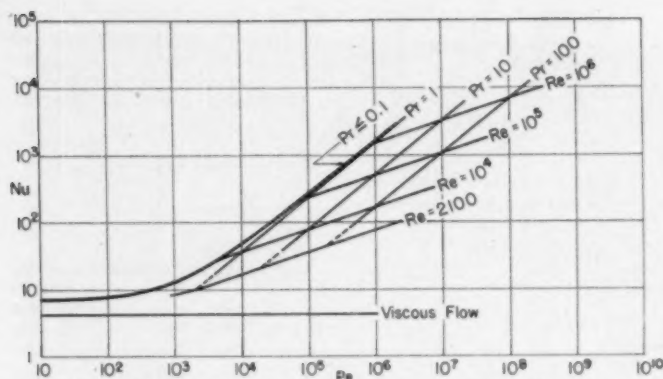
Fig. 2. Nu for turbulent and viscous flow vs. Pe, Pr and Re using Equations (5), (21), and (23).

*Comparison with Experimental Values for Liquid Metals.* Few heat-transfer data are available using liquid metals. Styrikovitch and Semenovker (13) report some data on mercury as do Musser and Page (8). These results are all lower than the values predicted by Equation (23). However, in each case the liquid did not wet the wall of the tube.

To obtain experimental values with liquid metals where the liquid did wet the wall, equipment was set up to circulate 50 wt. % sodium potassium alloy through a double-tube heat exchanger of nickel. Dimensions of the heat exchanger are given in Table 4.

This alloy, which melts at about 15° C., is known to wet nickel. It was operated to temperatures up to about 950° F. without mishap.

The predicted over-all heat-transfer coefficients were compared with the experimental values. Results of the comparisons are shown in Figure 3.

While agreement is not perfect, lack of accurate knowledge of the physical properties and experimental difficulties probably account for the discrepancy, and it is believed that the confirmation is good enough to propose Equations (23) and (24) as good working formulas for predicting heat transfer in liquid metals.

It may be pointed out that Equation (24) applies only when the inside and outside radii are almost equal. Recent experimental results with sodium potassium by Werner, King, and Tidball (15) tend to confirm Equation (23), but are high when compared with Equation (24). Satisfaction of both sets of annulus data is obtained when the differences in annulus dimensions are used with unpublished relationships developed by R. V. Bailey (now associated with department of chemical engineering, University of Mississippi) at Oak Ridge National Laboratory, who used, in part, annulus velocity data supplied by J. G. Knudsen and D. L. Katz of the University of Michigan.

It appears, upon comparison of work with wetting and nonwetting fluids, that the slight thermal resistance due to nonwetting becomes important with liquid metals, whereas in ordinary fluids this resistance is masked by the thermal resistance in the fluid itself. Considerably more work is needed to establish this point, but evidence is conclusive that a marked electrical resistance is obtained under nonwetting conditions, and it is believed that appreciable thermal resistance exists as well.

### TABLE 3

COMPARISON OF EQUATION (24) WITH RESULTS OF HARRISON AND MENKE FOR ANNULI

| Pe | Nu according to Harrison and Menke for Pr value of | | | Nu using Approximate Equation (24) |
|---|---|---|---|---|
| | 0.005 | 0.01 | 0.05 | |
| 100 | - | 5.55 | - | 5.6 |
| 500 | 8.0 | - | - | 7.4 |
| 1,000 | - | 9.5 | - | 9.3 |
| 5,000 | 19.6 | - | 21.6 | 20.8 |
| 10,000 | 31.2 | - | - | 32.6 |

### TABLE 4

SPECIFICATIONS FOR EXPERIMENTAL HEAT EXCHANGERS

**Heat Exchanger A**

Material: Commercially pure nickel

Length: 48 inches; Mounted vertically

| Inner Tube | Outer Tube |
|---|---|
| O.D. = 0.500 inches | O.D. = 0.759 inches |
| I.D. = 0.432 inches | I.D. = 0.715 inches |
| Wall = 0.034 inches | Wall = 0.022 inches |

**Heat Exchanger B**

Material: Commercially pure nickel

Length: 69 inches; Mounted horizontally

| Inner Tube | Outer Tube |
|---|---|
| O.D. = 0.757 inches | O.D. = 1.001 inches |
| I.D. = 0.703 inches | I.D. = 0.931 inches |
| Wall = 0.027 inches | Wall = 0.035 inches |

**Heat Exchanger C**

Material: Commercially pure nickel

Length: 33 inches; Mounted horizontally

| Inner Tube | Outer Tube |
|---|---|
| O.D. = 0.500 inches | O.D. = 0.754 inches |
| I.D. = 0.434 inches | I.D. = 0.684 inches |
| Wall = 0.033 inches | Wall = 0.035 inches |

**Heat Exchanger D**

Material: Commercially pure nickel

Length: 69 inches; Mounted horizontally

| Inner Tube | Outer Tube |
|---|---|
| O.D. = 0.500 inches | O.D. = 0.754 inches |
| I.D. = 0.434 inches | I.D. = 0.684 inches |
| Wall = 0.033 inches | Wall = 0.035 inches |

multiplying the Reynolds modulus by the Prandtl modulus.

Tables 1 and 2 compare results using Equation (23) with the values computed from Equation (19) and with those calculated by Martinelli (7).

For values of *Pr* equal to or greater than one in the system under discussion, the results from Equation (19) would correspond to those using the Karman heat-transfer equation (4), if his velocity distribution equations are used. The computed results above Pr of unity would then fit experimental results up to *Pr* about 25. Use of Reichardt's (11) velocity distribution with a modification of Equation (19) or use of the corrections proposed by Boelter et al, should give results comparable to empirical values over the entire range of Prandtl modulus above 1.

A plot of Equation (23) is given in Figure 2. This applies for values of *Pr* less than one. Lines for *Pr* of 1 and above are obtained from the Colburn (2) equation, Equation (5).

The abrupt change in heat-transfer coefficient, particularly at higher Reynolds modulus, will be noted as the Prandtl modulus drops below unity.

For comparing experimental results with the theoretically derived equation, it was found desirable to have an expression for heat transfer with liquid metals in annuli. For this purpose, the work of Harrison and Menke (3) was investigated. It was found that their calculated results for parallel plates with heat passing through only one side were about seven tenths of the value predicted from Equation (23) using the concept of hydraulic diameter.

As a result, the following equation may be assumed to apply to annuli which have a ratio of outer to inner diameter close to unity:

$$Nu_{ann.} = 4.9 + .0175 Pe^{.8} \quad (24)$$

## Conclusion

Liquid metals represent an essentially untapped field of heat-transfer media with high boiling point, high resistance to thermal decomposition and unusually high heat-transfer ability. A simple means of calculating heat transfer in liquid metals has been developed, although additional experimental work is needed. In the course of experimental work in this field, small-scale handling methods have been developed. It is hoped that these methods can be scaled up to industrial size so that the potentialities of liquid metals as heat-transfer media can be fully realized.

## Notation

$A_w$ = area on surface of a unit length of tube, area

$c$ = specific heat, heat/(mass) (temperature)

$D$ = diameter of tube, length

$E$ = eddy conductivity of heat, heat/(time)(area)(temperature/length)

$f$ = Fanning friction factor

$h$ = heat-transfer coefficient, heat/(time)(area)(temperature)

$k$ = molecular conductivity of heat, heat/(time)(area)(temperature/length)

$K$ = total conductivity of heat, heat/(time)(area)(temperature/length)

$q$ = heat flow toward the tube center, heat/time

$r$ = distance from tube center, length

$S$ = relative distance from tube center, $\dfrac{r}{r_w}$

$t$ = temperature

$u$ = velocity, length/time

$U$ = over-all heat-transfer coefficient, heat/(time) (area) (temperature)

$V$ = relative velocity = $\dfrac{u}{u_m}$

$W$ = flow rate, weight/time

$z$ = distance along tube axis, length

$N_u$ = Nusselt modulus = $\dfrac{hD}{k}$

$Pe$ = Peclet modulus = $\dfrac{DC\rho u_m}{k}$

$Pr$ = Prandtl modulus = $\dfrac{c\mu}{k}$

$Re$ = Reynolds modulus = $\dfrac{D\rho u_m}{\mu}$

**GREEK**

$a$ = $\epsilon_H/\epsilon_M$

$\epsilon$ = eddy diffusivity, (length)$^2$/time

$\theta$ = angular displacement, radians

$\mu$ = absolute viscosity, mass/(length)(time)

$\nu$ = kinematic viscosity, (length)$^2$/time

$\rho$ = density, mass/(length)$^3$



$$\dfrac{U_{Obs.}}{U_{Pred.}}$$

$(Pe_{Ann.} = 0.36\ Pe_{Tube})$



$$\dfrac{U_{Obs.}}{U_{Pred.}}$$

$(Pe_{Ann.} = 0.42\ Pe_{Tube})$
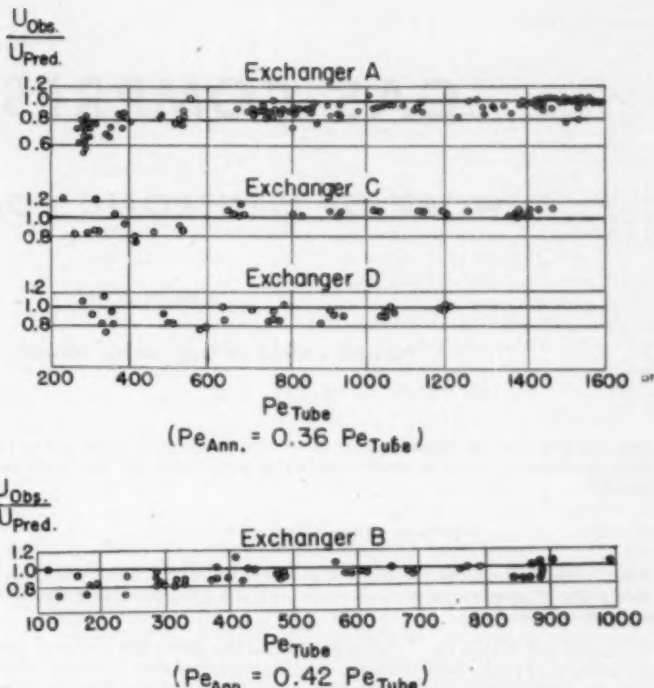
Fig. 3. Comparison of observed over-all coefficient with predicted over-all coefficient.

**SUBSCRIPTS**

$H$ = of heat

$m$ = mean, (in the case of fluid temperature, flow mean)

$M$ = of momentum

$q$ = where heat flow toward center is $q$

$t$ = where fluid temperature is $t$

$vis$ = viscous flow

$w$ = at wall

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*(Presented at Forty-second Annual Meeting, Pittsburgh, Pa.)*

# GAS COMPRESSORS

## WORK OF ISENTROPIC COMPRESSION

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The formula for the isentropic work of compression of ideal gases has been modified to yield a simple empirical expression for use with real gases:

$$-W_s = \frac{k}{k-1} RT_1 [(P_2/P_1)^{z(k-1)/k} - 1]$$

where $-W_s$ is the work per mole of gas handled, and $k$ and $z$ are respectively the ideal-gas specific heat ratio and the compressibility factor at suction conditions.

Edmister and McGarry (3) have calculated the isentropic work of compression in 72 cases, both with the aid of thermodynamic tables or charts, and by their generalized isentropic exponent method. The proposed formula has been tested in all these cases and has been found to give results in reasonably good agreement with both methods.

It is recommended that the proposed formula be used with fluids for which thermodynamic diagrams or tables are not available, when a more rapid procedure for calculating isentropic work is desired than the methods developed by York and by Edmister and McGarry.

CALCULATION of the work of isentropic compression is important in the design of gas compressors. This work has been widely adopted as a standard of comparison in the evaluation of compression efficiencies.

If ideal gas laws are assumed and the variation of specific heat with temperature is disregarded, the theoretical work of isentropic compression per mole of gas handled is given by the formula,

$$-W_s = \frac{k}{k-1} RT_1 [(P_2/P_1)^{(k-1)/k} - 1] \tag{1}$$

as shown in standard texts in engineering thermodynamics.

When deviation from ideal gas laws is appreciable and thermodynamic diagrams or tables are available, the theoretical work is readily found from the enthalpy change along an isentropic path. This procedure is of limited applicability, because thermodynamic diagrams and tables are available for only a relatively small number of substances.

Alternative procedures are based on the law of corresponding states and involve the use of generalized correlations. These are the method recommended by York (7), which involves successive approximation with the aid of a generalized entropy-pressure chart, and the generalized isentropic exponent method developed by Edmister and McGarry (3). Both methods are considerably more laborious than calculations for ideal gases with Equation (1).

Accordingly, simple modifications of Equation (1), for application to real gases, are still of interest to those engaged in compressor design. One such modification of Equation (1) was proposed by Laverty (4), who applied the correction for deviation from ideal gas laws to the volume of the gas taken in by the compressor. According to Laverty, for a real gas Equation (1) becomes,

$$-W_s = \frac{k}{k-1} zRT_1 [(P_2/P_1)^{(k-1)/k} - 1] \tag{2}$$

where $z$ is the compressibility factor of the gas at suction conditions. It is found in practice that Equation (2) undercorrects for ideal gas law deviations, so that calculated values are usually high and on the conservative side.

*Proposed Method.* It is sometimes assumed that the change of state of a real gas during compression may be represented by

$$PV^n = \text{constant} \tag{3}$$

where $n$ is a constant to be determined from the actual behavior of the gas in the compressor. A process represented by Equation (3) is known as a polytropic process. It follows from Equation (3) that the reversible work of polytropic compression is:

$$-W_s = \int_{P_1}^{P_2} VdP$$

$$= \frac{n}{n-1} P_1V_1 [(P_2/P_1)^{(n-1)/n} - 1] \tag{4}$$

Laverty's Equation (2) for the isentropic compression of a real gas follows from Equation (4) if $n$ is replaced with $k$. A different empirical modification of Equation (4) is proposed here. In Equation (4) $n/(n-1)$ is replaced with $k/z(k-1)$. Thus modified, Equation (4) becomes:

$$-W_s = \frac{k}{z(k-1)} P_1V_1 [(P_2/P_1)^{z(k-1)/k} - 1] \tag{5}$$

The compressibility factor $z$ and the ideal-gas specific heat ratio $k$ in Equation (5) are to be evaluated at suction conditions. Equation (5) may also be

## TABLE 1

### Demonstration of Proposed Method

| Compound | Initial | | | Final | Isentropic Work | | | |
|---|---|---|---|---|---|---|---|---|
| | Temp. °F. | Press. Lb./sq.in. absolute | Compr. Factor z | Press. Lb./sq.in. absolute | Obs. | Calc. | E.&Mc. | %Dev. |
| Water | 570 | 500 | 0.904 | 2000 | 2980 | 2974 | 2907 | - 0.2 |
| " | 700 | 400 | .953 | 1600 | 3545 | 3542 | 3549 | - 0.1 |
| " | 525 | 600 | .860 | 3000 | 3180 | 3195 | 3086 | + 0.5 |
| " | 400 | 150 | .946 | 1300 | 4520 | 4500 | 4501 | - 0.4 |
| Ammonia | 150 | 28 | .988 | 138 | 2270 | 2295 | 2277 | + 1.1 |
| " | 150 | 135 | .938 | 300 | 985 | 990 | 1005 | + 0.5 |
| " | 150 | 93 | .960 | 300 | 1540 | 1552 | 1490 | + 0.8 |
| " | 150 | 60 | .974 | 250 | 2035 | 2040 | 2070 | + 0.2 |
| Carbon Dioxide | 41 | 50 | .976 | 200 | 1525 | 1520 | 1520 | - 0.3 |
| " | -23 | 150 | .878 | 600 | 1320 | 1232 | 1221 | - 6.6 |
| " | -21 | 75 | .943 | 500 | 2025 | 1950 | 1941 | - 3.7 |
| " | 8 | 300 | .703 | 1150 | 1144 | 1121 | 1139 | - 2.0 |
| Carbon Dioxide | 50 | 478 | .747 | 1000 | 775 | 596 | 653 | -23.1 |
| " | 0 | 260 | .812 | 850 | 995 | 988 | 978 | - 0.7 |
| " | 50 | 300 | .852 | 885 | 1302 | 1041 | 1030 | -20.0 |
| " | 0 | 52 | .9665 | 363 | 2150 | 2162 | 2244 | + 0.6 |
| Hydrogen Sulfide | 60 | 147 | .894 | 1020 | 1908 | 2240 | 2274 | +17.4 |
| " | 180 | 147 | .948 | 1030 | 2705 | 2948 | 2875 | + 9.0 |
| " | 240 | 147 | .962 | 588 | 2220 | 2177 | 2211 | - 1.9 |
| " | 124 | 294 | .846 | 1030 | 1182 | 1402 | 1530 | +18.6 |
| Sulfur Dioxide | 142 | 150 | 0.885 | 1000 | 2350 | 2375 | 2320 | +1.1 |
| " | 200 | 60 | .965 | 400 | 2950 | 2914 | 2894 | -1.2 |
| " | 191 | 100 | .834 | 500 | 2310 | 2280 | 2263 | -1.3 |
| " | 150 | 40 | .970 | 400 | 3380 | 3447 | 3445 | +2.0 |
| Methane | -170 | 80 | .913 | 400 | 1026 | 1034 | 1026 | +0.8 |
| " | -120 | 100 | .940 | 300 | 805 | 800 | 808 | -0.6 |
| " | - 90 | 100 | .969 | 300 | 885 | 899 | 887 | +1.6 |
| " | - 70 | 80 | .971 | 250 | 1011 | 986 | 1018 | -2.5 |
| Ethylene | 20 | 294 | .790 | 882 | 938 | 908 | 878 | -3.2 |
| " | 0 | 147 | .984 | 882 | 1720 | 1723 | 1750 | +0.2 |
| " | 100 | 147 | .947 | 735 | 1925 | 1961 | 1968 | +1.9 |
| " | 120 | 147 | .952 | 588 | 1670 | 1720 | 1774 | +3.0 |
| Ethane | 0 | 100 | .892 | 800 | 2230 | 2005 | 2026 | -10.1 |
| " | 100 | 100 | .950 | 800 | 2490 | 2570 | 2543 | +3.2 |
| " | 220 | 100 | .973 | 500 | 2330 | 2348 | 2347 | +0.8 |
| " | 270 | 40 | .993 | 125 | 1766 | 1763 | 1793 | -0.2 |
| Propane | 73 | 50 | .930 | 160 | 1192 | 1220 | 1084 | +2.3 |
| " | 109 | 40 | .958 | 180 | 1560 | 1613 | 1574 | +3.4 |
| " | 75 | 60 | .917 | 190 | 1092 | 1193 | 982 | +9.2 |
| " | 80 | 60 | .920 | 300 | 1700 | 1728 | 1611 | +1.6 |
| n-Butane | 180 | 58.8 | .920 | 294 | 1770 | 1990 | 1876 | +12.4 |
| " | 250 | 117.8 | .883 | 514 | 1820 | 1966 | 1980 | +8.1 |
| " | 320 | 117.8 | .923 | 551 | 2155 | 2308 | 2291 | +7.1 |
| " | 400 | 117.8 | .947 | 588 | 2570 | 2722 | 2754 | +5.9 |

written in a form resembling Equation (1):

$$-W_s = \frac{k}{k-1} RT_1 [(P_2/P_1)^{z(k-1)/k} - 1]$$

(6)

where $-W_s$ is the isentropic work per mole of gas handled by the compressor, and $z$ and $k$ are evaluated at suction conditions, as in Equation (5).

Consideration has been given to extending the proposed method to the calculation of the temperature of the gas, $T_2$, at discharge conditions. The following relation has been derived from Equation (3):

$$(z_2 T_2 / z_1 T_1) = (P_2/P_1)^{z(k-1)/k}$$

(7)

In applying Equation (7), $z$ and $k$ in the exponent have been evaluated at suction conditions. However, Equation (7) is not recommended, since it does not always yield accurate results, particularly if the discharge temperature of the gas is considerably above its critical temperature. Accordingly, the proposed method should not be used to predict the isentropic temperature change.

When, however, the isentropic work rather than the isentropic temperature change is of major interest, the simplicity of the proposed method has much to recommend it. Calculations with the aid of Equation (6) are rapid, and the accuracy of the results is believed to be of the same order as in the method of Edmister and McGarry. These authors have published a detailed demonstration of their method (3), so that comparison with other procedures is facilitated. Accordingly, Equation (6) has been tested for the 72 isentropic paths used by Edmister and McGarry in presenting their generalized isentropic exponent method.

Results of these calculations are shown in Table 1. Following Edmister and McGarry, values for the isentropic work obtained by them from thermodynamic charts or tables are listed as observed values. The calculated values in Table 1 are the results obtained from Equation (6). The per cent deviations of the calculated from the observed values are tabulated in the last column of Table 1. The average of these 72 deviations, without regard to signs, is 3.2 per cent. The third column under isentropic work in Table 1 gives the results obtained by Edmister and McGarry with the generalized isentropic exponent method. The average deviation of the results calculated with Equa-

tion (6) from those of Edmister and McGarry is 2.8%. The average deviation of Edmister's and McGarry's values from observed values is 4.1%.

Inspection of values for isentropic work in Table 1 shows that there is reasonably good agreement between results obtained with Equation (6) and observed values, except for two carbon dioxide paths and two hydrogen sulfide paths. However, the method of Edmister and McGarry likewise yields excessively large deviations from observed values for these four paths. It has been pointed out by Edmister and McGarry (3) that published thermodynamic tables and charts are not consistently reliable for all fluids.

*Discussion of Procedure.* Some care had to be exercised in selecting the appropriate compressibility factor correlation for use with Equation (6), since in most instances suction conditions corresponded to relatively low reduced temperatures and pressures, for which most published $z$-charts are not satisfactory. Thomson's nomograph of compressibility factors for vapors (2, 5) was found suitable and was used for reduced presures above 0.07 and for reduced temperatures below 1.0. For reduced pressures below 0.07 and for reduced temperatures both above and below 1.0, the generalized low-pressure compressibility factor chart of Brown, Katz, Oberfell and Alden (1) was used. Where the range of this chart overlaps that of Thomson's nomograph, these two correlations were found to agree closely. For reduced temperatures above 1.0 and for reduced pressures above 0.07 another generalized compressibility factor chart of Brown, Katz, Oberfell and Alden (1), with a range of reduced pressures up to 1.6, was used. In Table 1 are listed values of the compressibility factor obtained from these correlations and used in this study. These values have been checked against the low-pressure compressibility factor chart published in the Worthington Research Bulletin (6) and have been found to be in reasonably good agreement with it.

Values of $k$ were calculated by the formula, $k = 1 + R/(C_p^\circ - R)$. The values of $C_p^\circ$ were obtained by linear interpolation in the table of ideal-gas heat capacities compiled by Edmister and McGarry for substances covered in their study (3). A 10-in. log-log slide rule was used in all calculations.

## Notation

(Any consistent units)

$C_p^\circ$ = molal heat capacity at constant pressure for ideal gas state

### TABLE 1 (Continued)

| Compound | Initial | | | Final | Isentropic Work | | | |
| | Temp. °F. | Press. Lb./sq.in. absolute | Compr. Factor z | Press. Lb./sq.in. absolute | Obs. | Calc. | E.&Mc | %Dev. |
|---|---|---|---|---|---|---|---|---|
| Methyl Chloride | 171 | 100 | 0.923 | 260 | 1165 | 1202 | 1205 | +3.2 |
| " | 148 | 100 | .915 | 260 | 1140 | 1150 | 1123 | +0.9 |
| " | 60 | 20 | .971 | 200 | 2865 | 2948 | 2908 | +2.9 |
| " | 170 | 30 | .979 | 220 | 2900 | 2951 | 2923 | +1.8 |
| CCl₃F (F-11) | 343 | 20 | .986 | 65 | 1950 | 1960 | 1944 | +0.5 |
| " | 311 | 25 | .980 | 65 | 1498 | 1500 | 1632 | +0.1 |
| " | 220 | 28 | .964 | 65 | 1140 | 1140 | 1139 | 0.0 |
| " | 220 | 13.5 | .983 | 65 | 2380 | 2250 | 2185 | −5.5 |
| CCl₂F₂ (F-12) | 175 | 39 | .966 | 220 | 2320 | 2302 | 2276 | −0.8 |
| " | 140 | 34 | .964 | 160 | 1910 | 1928 | 1940 | +0.9 |
| " | 225 | 45 | .970 | 145 | 1630 | 1535 | 1632 | −5.8 |
| " | 98 | 46 | .935 | 220 | 1815 | 1760 | 1716 | −3.0 |
| CHCl₂F (F-21) | 300 | 26 | .9835 | 68.5 | 1520 | 1519 | 1436 | −0.1 |
| " | 253 | 25 | .980 | 100 | 2100 | 2090 | 2002 | −0.5 |
| " | 200 | 20 | .9796 | 110 | 2425 | 2434 | 2425 | +0.4 |
| " | 190 | 34.5 | .9626 | 110 | 1535 | 1548 | 1499 | +0.8 |
| CHClF₂ (F-22) | 80 | 52.5 | .940 | 200 | 1462 | 1487 | 1456 | +1.7 |
| " | 80 | 77 | .913 | 220 | 1100 | 1108 | 1079 | +0.7 |
| " | 90 | 40 | .959 | 240 | 2090 | 2140 | 2131 | +2.4 |
| " | 140 | 50 | .963 | 260 | 2080 | 2122 | 2104 | +2.0 |
| C₂Cl₃F₃ (F-113) | 241 | 25 | .959 | 70 | 1408 | 1419 | 1288 | +0.8 |
| " | 292 | 25 | .968 | 70 | 1500 | 1536 | 1468 | +2.4 |
| " | 360 | 25 | .976 | 70 | 1690 | 1687 | 1547 | −0.2 |
| " | 442 | 25 | .982 | 70 | 1874 | 1863 | 1829 | −0.6 |
| C₂Cl₂F₄ (F-114) | 292 | 27 | 0.978 | 83 | 1709 | 1699 | 1696 | −0.6 |
| " | 170 | 20 | .970 | 85 | 1815 | 1847 | 1781 | +1.8 |
| " | 230 | 23 | .975 | 85 | 1795 | 1821 | 1792 | +1.4 |
| " | 330 | 18 | .9876 | 85 | 2505 | 2520 | 2490 | +0.6 |

$k = C_p^\circ/(C_p^\circ - R)$ = ratio of specific heats for ideal gas state

$n$ = constant exponent in polytropic process

$P$ = absolute pressure

$R$ = ideal gas constant

$T$ = absolute temperature

$V$ = molal volume

$-W_s$ = isentropic work of compressor per mole of gas handled

$z = PV/RT$ = compressibility factor

Subscripts:

$_1$ = suction conditions

$_2$ = discharge conditions

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# STEADY-STATE TRANSFER PROBLEMS

## GRAPHICAL SOLUTIONS

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MANY chemical engineering proc-
esses involve the steady-state
transfer of some entity between two
flows of carrier materials. Typical of
such processes are countercurrent
leaching, extraction, adsorption, distil-
lation, and heat transfer such as in the
preheating or cooling stages of a fluo-
solids reactor. A McCabe-Thiele dia-
gram can be used for solving these proc-
esses if the carrier constituents are each
totally transferred from stage to stage
in their respective directions. More
often, however, one or both carrier con-
stituents may recirculate between
stages, either through entrainment or
through partial miscibility of one in the
other. Thus in countercurrent decanta-
tion a certain fraction of the solvent
returns with the settled solids to the pre-
ceding stage, rather than advancing
with the main body of the solvent to
the succeeding stage. In liquid-liquid
extraction the two solvents may be par-
tially miscible, and be distributed be-
tween both overflow and underflow
streams.

This paper describes a generalization
of the McCabe-Thiele type of diagram
which permits solution of processes con-
taining recirculation of carrier mater-
ials, and which retains the convenience
of a straight operating line. As would
be expected of a generalization, it re-
duces to the original McCabe-Thiele
method under conditions for which the
latter is applicable. Also it yields con-
structions essentially identical to those
of Ravenscroft (3) when used for solv-
ing problems to which the Ravenscroft
method is applicable.

The generalized method is similar to
the original McCabe-Thiele method in
that it is characterized by an equilibrium
curve, a straight operating line, and a
system of construction lines drawn be-
tween the equilibrium curve and the
operating line. In the original McCabe-
Thiele method the construction lines are

horizontal and vertical. In the general-
ized method, each construction line is
shown to describe the composition of
one of the process streams, and to have
a slope determined by that composition.

Derivations which follow are carried
out in terms which are actually abstract
and generalized. However, in order to
avoid obscurity, the notation used is
based on the model of liquid-liquid ex-
traction. While this gives a certain con-
creteness in the presentation of the
method, the reader must be prepared
eventually to accept such substitutions
as that of heat for either the "solute"
or the "solvent" of the derivations. Also
specific cases will be found where the
solvent of the derivation turns out to be
donating solute instead of extracting it.

The notation is adopted in part from
that of Varteressian and Fenske (5),
and in part from that used by Badger
and McCabe (2) for leaching and ex-
traction. In almost every case the sym-
bols have a less restricted meaning. An
eclectic notation seemed necessary be-
cause no single set of conventional
notation was found which was suitable.
Figure 1 is a generalized flow dia-
gram of a countercurrent transfer sys-
tem. The flows comprise three constitu-
ents. The flow of the first constituent

in the overflow streams is designated by
$A'$, while the flow of the same con-
stituent in the underflow streams is de-
noted by $a'$. Flows of a second con-
stituent are correspondingly designated
by $C'$ and $c'$, those of a third by
$S'$ and $s'$. Quite arbitrarily, the first
constituent, corresponding to flows $A'$
and $a'$, is considered to be the solute
or entity which is being transferred.
The choice is arbitrary because there is
no inherent difference initially in the
mathematical status of any of the con-
stituents. Both the other constituents
are then carriers, but for purposes of
differentiation, the second constituent,
corresponding to $C'$ and $c'$, is called the
"carrier," and the third one is called
the "solvent."

In this paper, constituents are defined
as any entities which are conserved
throughout the system. Usually at least
two of the three will consist of the mass
of some material component or group of
components. The third may often com-
prise a quantity of heat.

The upper streams in Figure 1 are
arbitrarily named "overflow" streams,
and all properties relating to them are
designated by capital letters. Overflow
streams are made of a "light" or over-
flow phase, plus any entrainment of a
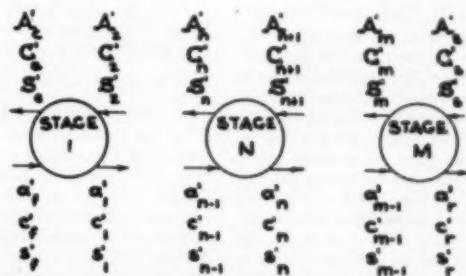


Fig. 1. Generalized countercurrent transfer system.
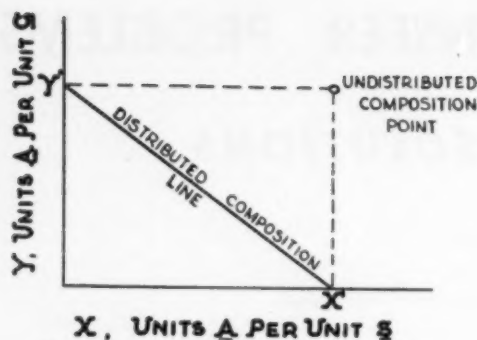
Fig. 2. Alternative methods for plotting a stream composition.
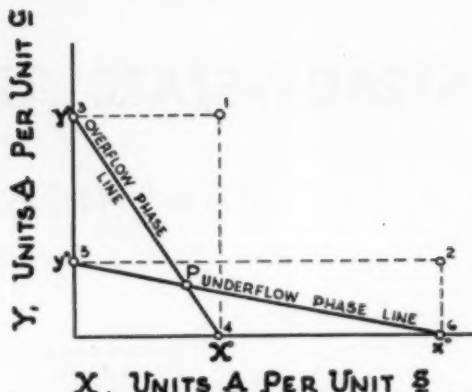


Fig. 3. Construction for locating points on equilibrium line.

"heavy" or underflow phase. Lower case letters are used to denote properties relating to the lower "underflow" streams, which comprise an underflow phase plus any entrainment of overflow phase. Undistributed properties relating to any single stream as a whole are identified with superscript prime ($'$). Coordinates relating to the equilibrium line are marked with an asterisk ($*$), and undistributed properties relating to the phases are marked with the superscript ($^{\circ}$).

Stage $M$ is the final one in the process element under consideration; stage $N$ represents any unit. Subscripts denote the stage from which streams flow. Subscripts and notation relating to terminal flows to and from the system are derived from the model of liquid-liquid extraction. Thus subscript $f$ derives from "feed," $e$ from "extract," $s$ from "fresh solvent," and $r$ from "raffinate." Naming these streams on the basis of a specific model does not detract from the generality of the presentation, and is of aid in remembering the significance of the symbols.

$X$ is the ratio of $A$ to $S$; $Y$ is the ratio of $A$ to $C$, and $W$ is the ratio of $S$ to $C$ within any given process material or stream. (See Notation.)

## Derivation of Basic Constructions

The three basic elements of a Mc-Cabe-Thiele diagram are the operating line, equilibrium line, and the series of construction lines. It will first be shown that in a distributed method of plotting, the construction lines actually correspond to individual composition plots, and hence that every stream in the process can be represented on the diagram by such a construction or composition line. Next the equation of the operating line will be developed. Finally the significance and location of the equilibrium line will be considered.

*Construction Lines, Distributed and Undistributed Concentration Plots.* Figure 2 shows a coordinate system which subsequently will be shown to be consistent with that of the original Mc-Cabe-Thiele diagram. On it are shown two methods of plotting, by way of example, the composition of an overflow stream. In the first or undistributed case, the ratio of all the $A'$ in the stream to $S'$, (namely $X'$) is plotted against the ratio of all the $A'$ to $C'$ (namely $Y'$). This yields the single point ($X'Y'$) to represent the undistributed composition of the stream. In the second case the constituent of flow $A'$ is considered as distributed between carrier flow $C'$ and solvent flow $S'$. Any part of $A'$ which is associated with $C'$ is considered not associated with $S'$ and vice versa. The situation can be visualized if $C'$ and $S'$ are temporarily considered as flows of immiscible solvents, between which the constituent of flow $A'$ may be arbitrarily partitioned. Then, from material balance

$$S'X + C'Y = A'$$

$$Y = -\frac{S'X}{C'} + \frac{A'}{C'} \qquad (1)$$

Thus the distributed concentration plot corresponding to any given overflow composition is a straight line with a slope equal to the ratio $-\dfrac{S'}{C'}$ or $-W'$. When all the constituent of flow $A'$ is considered as associated with $C'$, then it will be apparent that $X = o$ and $Y = Y'$. When it is all associated with $S'$, then $Y = o$ and $X = X'$. Therefore the intercepts of the line with the axes mark the coordinates of $X'$ vs. $Y'$. A vertical line represents a stream devoid of $C'$, while a horizontal one represents a stream devoid of $S'$.

It will be apparent that any composition, and hence any flow in the transfer system may be represented by such a distributed concentration line in the diagram. These lines are the construction lines of the proposed method and will be named for streams whose compositions they represent.

*The Operating Line.* The operating line is the locus of intersections of the lines representing overflow streams with those for the underflow streams which pass them in the process. Thus the intersection of the overflow line from any stage $N$ and the underflow line from stage $N - 1$ will lie on the operating line.

The equation of the overflow line from stage $N$ is:

$$S'_n X + C'_n Y = A'_n \qquad (2)$$

and the equation for the underflow line from stage $N - 1$ is:

$$s'_{n-1} X + c'_{n-1} Y = a'_{n-1} \qquad (3)$$

Combining (2) and (3) simultaneously, there is obtained for a line passing through the intersection of (2) and (3) the equation

$$(s'_{n-1} - S'_n)X + (c'_{n-1} - C'_n)$$
$$Y = (a'_{n-1} - A'_n) \qquad (4)$$

But since steady state has been specified, the net flow of any constituent past any point in the system must be constant. Therefore:

$$(a'_{n-1} - A'_n) = (a'_r - A'_e)$$
$$= (a'_f - A'_e) = \text{net } A$$

$$(c'_{n-1} - C'_n) = (c'_r - C'_e)$$
$$= (c'_f - C'_e) = \text{net } C$$

$$(s'_{n-1} - S'_n) = (s'_r - S'_e)$$
$$= (s'_f - S'_e) = \text{net } S$$
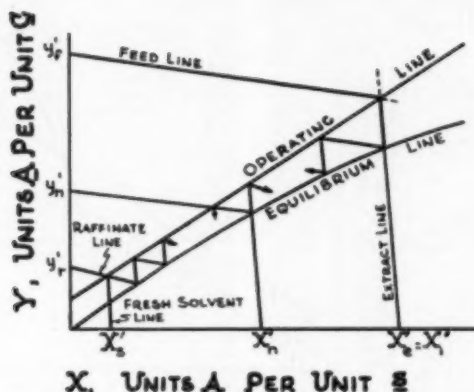
Fig. 4. Generalized McCabe-Thiele-type diagram.

Substituting in Equation (4), there is obtained as the locus of all possible such intersections the operating line:

$$Y = -\frac{(\text{Net } S)}{(\text{Net } C)} X + \frac{(\text{Net } A)}{(\text{Net } C)}$$

(5)

The operating line is straight, with a slope equal to minus (Net $S$)/(Net $C$). (Note the formal similarity of Equation (5) of the operating line to Equation (1) for composition lines.)

When the net flows of the constituents chosen as carriers are concurrent, the coefficient of $X$, and hence the slope of the operating line, will be negative. When the net flows are countercurrent, one of the terms will be negative and the slope of the operating line will be positive.

It should be noted that the straightness of the operating line is contingent upon two conditions only, namely, that the constituents are conserved, and that the operation is steady state.

*The Equilibrium Line.* When the two phases of a transfer system come into equilibrium with one another in each stage, the intersection of the overflow and underflow phase lines corresponding to any stage $N$ will lie on the equilibrium line. The overflow stream and underflow stream lines will also intersect on the equilibrium line. This is true even though the phases are not cleanly separated in the process, so that some of the overflow phase is entrained in the underflow stream, and vice versa. That entrainment does not affect the position of the intersections may be proved as follows:

The significance of any point on a composition distribution line is that the total stream can be resolved (mathematically) into two partial flows, one

consisting of $C$ with enough of $A$ to give the $Y$ coordinate of the point. The residue, consisting of $S$ and the remainder of $A$, would give the $X$ coordinate of the point. Any stream which could be divided into two partial flows with the same respective compositions, would yield a distributed concentration line passing through the same point. The overflow and underflow lines for a given stage have a point in common. Therefore they can each be resolved into two partial flows having concentrations corresponding to the intersection point. It will be apparent that any part of these partial flows may be interchanged between the overflow and underflow streams, without changing the coordinates of the intersection point. Entrainment is equivalent to such an interchange of partial flows. Therefore entrainment does not change the locus of the intersection points.

When the solvent and carrier are immiscible, the equilibrium line may be plotted in terms of undistributed concentrations, as in all other McCabe-Thiele methods. In this case there is no question of distributing the constituent of $A$ between the two other constituents $C$ and $S$ in either phase, because only one of the other two is present in each. The distribution lines for the phases will then have as equations $X = X^\circ$ and $Y = y^\circ$. Their intersection on the equilibrium line will have the coordinates $X^\circ$, $y^\circ$, which corresponds to the way such equilibrium lines have always been drawn in the past.

Although what has been stated will be true in perhaps all cases for which the proposed method will be found useful, it nevertheless represents a special case. The solvent and carrier will be more or less miscible in many liquid-liquid extraction problems, and the general case of distillation.

The equilibrium line is located in terms of distributed concentration. Whenever both carrier and solvent are present in a phase, the distributed constituent has to be properly partitioned between them, and the coordinates of points on the equilibrium line will not be equal to those of the undistributed compositions.

In case the solvent and carrier constituents are partially miscible, the coordinates of points on the equilibrium line may be determined by construction, or by calculation, from the compositions of the equilibrium phases. The construction for determining points on the equilibrium line is shown in Figure 3. Point (1) represents the undistributed composition $X^\circ$, $Y^\circ$ of the overflow phase, and point (2) represents the undistributed composition $x^\circ$, $y^\circ$ of the underflow phase in equilibrium with it. Line (3)-(4) is the distributed composition line for the overflow phase, and line (5)-(6) that for the underflow phase. Point $P$, their intersection, locates a point on the equilibrium curve. A sufficient number of points are thus located to permit drawing the equilibrium line.

The coordinates of points on the equilibrium curve may be calculated as follows:

The distributed composition line for the overflow phase may be expressed as:

$$S^\circ X^* + C^\circ Y^* = A^\circ \qquad (6)$$

And for the underflow phase

$$s^\circ X^* + c^\circ Y^* = a^\circ \qquad (7)$$

Solving (6) and (7) simultaneously, and substituting appropriately

$$X^* = \frac{Y^\circ - y^\circ}{W^\circ - w^\circ}$$

$$Y^* = \frac{W^\circ y^\circ - w^\circ Y^\circ}{W^\circ - w^\circ} \qquad (8)$$

Where:

$$w^\circ = s^\circ / c^\circ$$

and

$$W^\circ = S^\circ / C^\circ$$

Calculation of the equilibrium line from compositions of equilibrium phases is described above, and it is from such data that equilibrium lines have usually been calculated. Actually it is not necessary that the compositions of the pure phases be known. Any system of solute, solvent, and carrier which is in equilibrium may be split into any two dissimilar fractions, and a point on the equilibrium line found as the intersection of the distributed concentration lines for the two fractions.

*The Basic Diagram.* The elements of the generalized construction are assem-
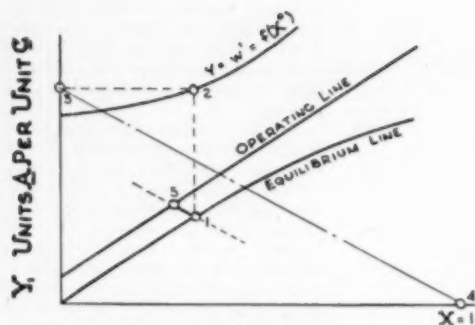
Fig. 5.
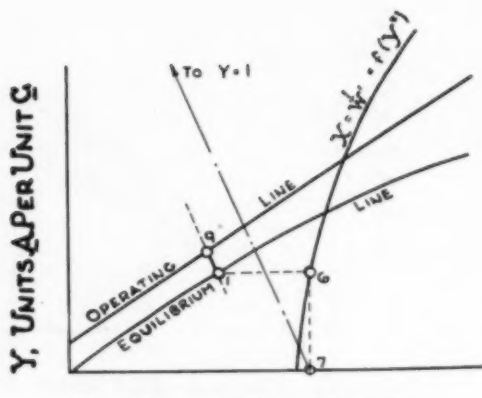


Fig. 5a.
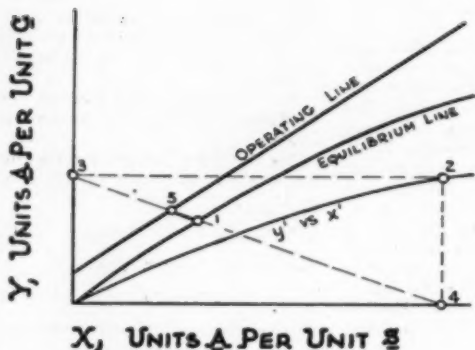


Fig. 6.
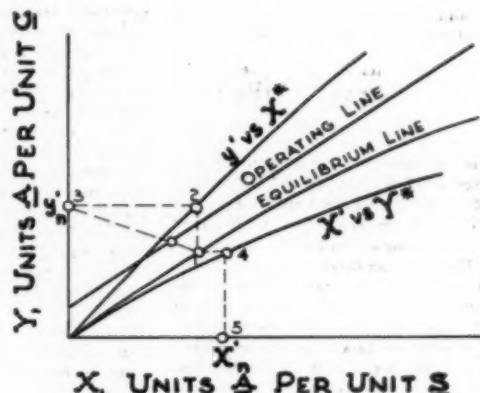


Fig. 7.

Figs. 5-7. Alternative methods for constructing slopes of flow lines.

bled and labelled in Figure 4. As shown above, the slopes of the various lines are as follows:

Slope of operating line $= -\dfrac{\text{Net } S}{\text{Net } C}$

Slope of overflow line from stage $N$ $= -W''_n$

Slope of underflow line from stage $N$ $= -w'_n$

Slope of feed line (underflow into stage 1) $= -w'_f$

Slope of extraction line (overflow from stage 1) $= -W''_e = -W''_1$

Slope of solvent line (overflow into stage $M$) $= -W''_s$

Slope of raffinate line (underflow from stage $M$) $= -w'_r = -w'_m$

### Constructions for Slopes of Flow Lines

In some cases the ratio of solvent to carrier, $W$, in the overflows and the underflows will be constant. In problems which can be solved by the original McCabe-Thiele method, for example,

the ratio will have the constant value infinity in the overflow streams and

zero in the underflow streams. The corresponding flow lines will then be vertical and horizontal respectively, and the construction becomes identical to that of McCabe and Thiele. In some other problems, such as those involving constant entrainment, the slopes of the

lines may be constant at some other values. However, in perhaps most cases the solvent-to-carrier ratio in the streams will be a function of their solute content. This function will usually be known through a series of experimentally obtained points.

Four alternative methods of constructing the flow lines with the proper slope will now be given. There will occur conditions under which each of these constructions becomes the most expedient.

The first method is illustrated in Figure 5. The ratio of solvent to carrier in the underflow streams is plotted as a function of the equilibrium curve abscissa, $X^*$, to give the curve labelled $Y = w' = f(X^*)$. To construct an underflow line from a point (1) on the equilibrium line corresponding to any stage $N$, point (2) is located on the $w'$ curve at $X = X^*_n$. The ordinate of point (2) measures the nega-

tive slope of the desired underflow line. This is projected onto the $Y$ axis to give point (3). A line drawn between point (3) and point (4) on the $X$ axis at $X = 1$ will have the same slope as the desired underflow line. The underflow line can then be drawn parallel to $(3)-(4)$ and through point (1).

Overflow lines can be constructed in exactly the same way. However, if there is little flow of carrier constituent $C'$ in the overflow streams, a curve $Y = W'' = f(X^*)$ might lie so far from the origin that it would not be practical to plot it. Alternatively a completely analogous construction may be made with a plot of the function

$$X = \frac{1}{W''} = f(Y^*)$$

This function has been shown on Figure 5a. To make the construction, point (6) is located on the curve

$$X = \frac{1}{W''} = f(Y^*)$$

at the ordinate $Y^*$ of point (1). The abscissa of point (6) is projected upon the $X$ axis to give point (7). A line drawn between point (7) and a point located on the $Y$ axis at $Y = 1$ gives the slope of the overflow line.

A second construction for flow lines is illustrated in Figure 6. It corresponds in principle to the constructions of Figures 2 and 3. In this method $y'$ is plotted as a function of $x'$, giving a curve which actually consists of an undistributed composition plot of the underflow streams. A similar curve, $Y'$ vs. $X'$ can be plotted for the overflow compositions. To construct, for example, an underflow line for any stage $N$, an undistributed composition point (2) is found on the $y'$ vs. $x'$ curve which will give a corresponding distributed concentration line $(3)-(4)$ passing through point (1) corresponding to stage $N$ on the equilibrium curve and through point (5) on the operating line. Overflow lines are constructed from a $Y'$ vs. $X'$ curve (not shown) in an obviously analogous manner. In practice the constructions are easy to make using a straight edge and a transparent right-angle triangle.

A third method, adopted from Ravenscroft is shown in Figure 7. The functions $y'$ vs. $X^*$ and $X'$ vs. $Y^*$ are plotted. To construct an underflow line corresponding to any stage $N$ from point (1) on the equilibrium curve, point (2) is found vertically above it on the $y'$ vs. $X^*$ plot. Point (2) projected onto the $Y$ axis locates point (3) at an end of the underflow line. The underflow line can now be drawn passing through points (1) and (3). The construction for an overflow line is made in an analogous manner by using the $X'$ vs. $Y^*$ plot, as shown by point (1), (4) and (5) on the diagram.

A fourth means of constructing flow lines which depends largely upon calculation is the semigraphical method of Ruth (4). In this method the $X$ coordinate at the intersection of the underflow line from stage $N$ with the operating line is calculated. Ruth's derivation of his basic equations is simple. The derivation outlined here is not as direct, but ties the results more obviously to the fully graphical methods thus far discussed.

The equation of the operating line from (5) is:

$$Y = -\frac{(\text{Net } S)}{(\text{Net } C)} X + \frac{(\text{Net } A)}{(\text{Net } C)}$$
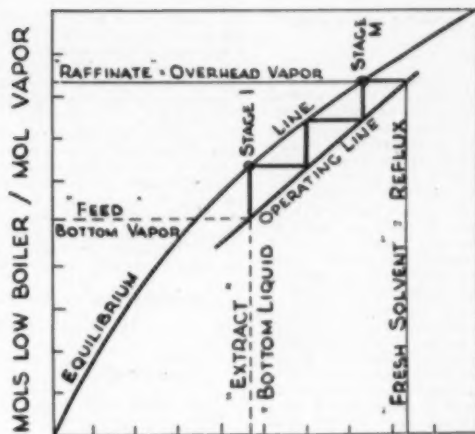


Fig. 8. Relation to classical McCabe-Thiele plot.

The equation of the underflow line from stage $n$ from (1) is:

$$s'_n X + c'_n Y = a'_n$$

solving these simultaneously, and substituting appropriately

$$X \text{ at intersection} = \frac{y'_n - \dfrac{(\text{Net } A)}{(\text{Net } C)}}{w'_n - \dfrac{(\text{Net } S)}{(\text{Net } C)}} \qquad (10)$$

The terms in parentheses can be evaluated from an over-all balance, and correspond to parameters of the operating line. The other terms $y'_n$ and $w'_n$ may be plotted as functions of $X^*_n$ and read from this plot.

In the special case that the overflow comprises no flow of carrier constituent, $C$, Equation (10) becomes:

$$X'_{n+1} = \frac{y'_n - \dfrac{(\text{Net } A)}{(\text{Net } C)}}{w'_n - \dfrac{(\text{Net } S)}{(\text{Net } C)}} \qquad (11)$$

(when overflows are devoid of $C$)

which is the case presented by Ruth.

When, furthermore, the underflows comprise no flow of solvent constituent, $S$, conditions correspond to those of the original McCabe-Thiele construction.

$$X'_{n+1} = \frac{\dfrac{(\text{Net } A)}{(\text{Net } C)} - Y^*_n}{\dfrac{(\text{Net } S)}{(\text{Net } C)}} \qquad (12)$$

(for original McCabe-Thiele diagram)

## Illustrative Applications

Many means are available for solving various countercurrent transfer problems. In simple cases, the use of a graphical method is often not warranted. In more complex cases the relative utility of the method presented compared with other graphical or semigraphical

methods will depend upon the individual problem, and upon the form and nature of the data from which it is to be solved.

Although the method here presented is completely general in nature, its application to such cases as liquid-liquid extraction, in which the carrier constituents are partially miscible, has not been studied and has not promised to be advantageous compared with other methods.

For leaching and solids extraction problems, the proposed method affords a clearer pictorialization of the effect of operating variables than the other graphical methods commonly used and is more flexible. Unlike the method of Ravenscroft, it is applicable when the solids are adsorbent for the solute. The method of Armstrong and Kammermeyer (1) is simpler to use if the ratio of solvent to solids is specified, but a new curve has to be drawn for every solution when this ratio is changed. Thus the proposed method should be simpler when the quantity of solvent appears as a variable. In such cases it may also be faster than the excellent semigraphical method of Ruth.

The constructions should be made on a large scale graph if precise problem solutions are desired, and are warranted by the accuracy of the data. This is equally true for any graphical method. Even in semigraphical ones, the graphical elements must be plotted on a large scale to obtain precision.

Three applications of the general method are discussed in the following: The first shows its relation to the original McCabe-Thiele method. The second shows its relation to the Ravenscroft method. The third shows its ap-

plication in a somewhat more complicated process.

*Rectification Diagram — Original McCabe-Thiele Method.* Since the general method is built upon the original McCabe-Thiele diagram, it is of interest to see how the latter fits into the general case. A part of a McCabe-Thiele rectification diagram is shown in Figure 8. The solute quantity, $A$ of the general case, here becomes identified as the moles of low boiling component. $C$ becomes identified as moles of vapor, and $S$ becomes identified as moles of liquid. In a general case, neither vapor nor liquid would qualify as a constituent under the special meaning given. There is no inherent reason why vapor cannot be converted to liquid in the process, and vice versa, so that neither entity necessarily needs to be conserved. However, in the original McCabe-Thiele method, conditions are specially defined so that condensation of one component is accompanied by a simultaneous vaporization of an equal number of moles of the other component. Therefore the vapor flow, when expressed in moles and only when so expressed, remains constant throughout a system between points of feed or withdrawal of material. Under these special conditions, the mole flow of vapor qualifies as a constituent, and therefore also the countercurrent mole flow of liquid.

In Figure 8 it will be apparent that the liquid phase, which because of the arbitrary choice of axis corresponds to what has been named the solvent constituent, is actually being stripped of the solute or low boiling constituent. Simultaneously the vapor phase or carrier is being enriched with solute. This reverses the direction of the constructions but does not otherwise affect them.

*Solvent Extraction of Soy Beans — Relation to Ravenscroft Method.* The following problem is solved in Badger and McCabe by the Ravenscroft method. It is also solved by Ruth, and the problem statement is from his paper. "Oil is to be extracted from meal by means of a continuous countercurrent extractor. The unit is to treat 2000 lbs. of meal per hour (based on oil-

free solids). The untreated meal contains 800 lbs. of oil and 50 lbs. of benzene. The fresh wash solution consists of 20 lbs. of oil dissolved in 1310 lb. of benzene/hr. The exhausted solids are to contain 120 lb. of unextracted oil. What number of units is required?"

The solute quantity $A$ of the general case is identified as pounds of oil. The carrier $C$ becomes pounds of meal on an oil- and benzene-free basis. The solvent $S$ corresponds to pounds of solution, or pounds of benzene plus oil. The problem assumes that the meal solids do not adsorb oil so $Y^*$ is at all times equal to zero, and the equilibrium line coincides with the $X$ axis.

### Benzene + Oil Balance

| | |
|---|---|
| Feed ................................. | $50 + 800 = 850$ lbs./hr. |
| Fresh solvent .......................... | $1310 + 20 = 1330$ lbs./hr. |
| Extracted solid ........................ | $\dfrac{-120}{x'_r} = \dfrac{-120}{.1185} = -1013$ lbs./hr. |
| Net = extract | $= 1167$ lbs./hr. |

Data necessary to the solution are given in Table 1.

Values of $y'$ have been plotted as a function of $X'$ in Figure 9. Since the solids are not adsorbent, it will be apparent that $X' = x'$.

The following concentrations may be calculated directly:

$$y'_f = \frac{800}{2000} = 0.40$$

$$x'_f = \frac{800}{800 + 50} = 0.941$$

$$X'_s = \frac{20}{1310 + 20} = 0.015$$

$$y'_r = \frac{120}{2000} = 0.060$$

These values permit construction of the feed line and the fresh solvent line immed-

iately. Since $y'$ is known for the extracted solids, and the function $y'$ vs. $x'$ has been plotted, $x'_r$ can be found and the raffinate line constructed by method 2 just described. Since the raffinate and the fresh solvent pass each other in the process, the intersection, $P$, of their distributed concentration plots gives a point on the operating line.

An oil and solution balance is now made to obtain $X'_e$:

### Oil Balance

| | |
|---|---|
| Feed ................. | $+800$ lbs./hr. |
| Fresh solvent ........ | $+\ 20$ lbs./hr. |
| Extracted solids ...... | $-120$ lbs./hr. |
| Net extract ............ | $\overline{700}$ lbs./hr. |

There is thus obtained for the extract line

$$X'_e = \frac{700}{1167} = 0.600$$

The extract line is now drawn. Its intersection, $Q$, with the feed line marks a second point on the operating line. The operating line can now be drawn through points $P$ and $Q$ and the stage constructions started. A vertical line extending up from point (1) intersects the $y'$ vs. $X'$ line at point (2), giving the value of $y'_1$. Point (2) projected to the $Y$ axis gives point (3), which lies at one end of the first stage underflow line. Point (1) marks the other end of the first stage underflow line since it lies at the intersection of the equilibrium line and the first stage overflow line (extract line). Therefore the first stage underflow line can be drawn, intersecting the operating line at point (4).

There is no recirculation of solids in any of the overflow streams, so their distributed concentration lines are vertical. Thus a vertical line through point (4) represents the second stage overflow line, and locates $X'_2$. This vertical line also intersects the $y'$ vs. $X'$ curve to locate point (5) and thence point (6) at the end of the second stage underflow line. Constructions are continued from stage to stage. It is seen that the stage 4 underflow essentially coincides with the desired raffinate composition. Therefore the number of units required for the extraction is four.

The stage constructions of Ravenscroft may be obtained from Figure 9 by rotating the $X$ axis in a clockwise direction to make the operating line horizontal. The $y'$ vs. $X'$ curve is not rotated with the rest of the system, because in the Ravenscroft method points on this curve are still projected rectangularly to the axes. Use of a skew coordinate system makes possible certain conveniences in over-all construction, but at the expense of making the method difficult to remember.



Fig. 9. Relation to Ravenscroft diagram.

### TABLE 1.—AMOUNTS OF OIL RETAINED IN UNDERFLOWS AT DIFFERENT OVERFLOW COMPOSITIONS

| $X'(=x')$ | $y'$ |
|---|---|
| 0.000 | 0.000 |
| 0.100 | 0.051 |
| 0.200 | 0.102 |
| 0.300 | 0.160 |
| 0.400 | 0.220 |
| 0.500 | 0.288 |
| 0.600 | 0.357 |
| 0.700 | 0.437 |

*Countercurrent Filtration.* The next
problem is hypothetical. It is made up
to illustrate solution of a countercurrent
filtration problem, and to contain most
of the complicating features which
might be met in countercurrent filtra-
tion. No published method has been
found for solving this type of problem.
The problem statement is as follows:

Find the amount of solvent necessary to
produce a saturated extract from an ad-
sorbent charged with an adsorbate, by
means of two stages of countercurrent fil-
tration. The equilibrium distribution of
adsorbate or solute between adsorbent and
solvent is as plotted in Figure 10, with the
solvent phase becoming saturated at
$X = 0.006$. The feed contains 500 lbs. of
adsorbent/hr., an equal quantity of solvent,
and 6 lbs. of solute. The ratio of solute
to solvent in the fresh solvent stream,
$X_s' = 0.001$. The filter cake dilution or
ratio of solvent (solute free) to adsorbent
solids (solute free) in the discharging
filter cakes is given as 0.5. The displace-
ment efficiency of the filter cake washes
is given as an experimentally determinate
function of $F$, the amount of solvent in
the wash applied to the cake per unit
weight of adsorbent, as graphed in Figure
11. Displacement efficiency $E$, is here de-
fined as the per cent of the solvent remain-
ing entrained in the washed cake which
comes from wash solution.

Constituent quantity $A$ becomes identi-
fied as pounds of solute, quantity $C$ as
pounds of adsorbent solids, and quantity $S$
as pounds of solvent.

Countercurrent filtration may be repre-
sented as shown in Figure 12. Dotted lines
indicate the stage boundaries. The adsorb-
ent is transferred in toto from stage to
stage as filter cake solids. Liquor flows,
however, recirculate. If it now be assumed
that equilibrium is reached in the repulpers,
and that the filtrate used on the wash
sprays of the filters does not equilibrate
with the solids on the filter, but merely
acts as a displacing wash, the system can
be solved readily. These assumptions are
usual for any solution.

The net flow of solvent towards the left
($-$net $S$) is equal to total solvent in wash
—total solvent entrained in the cake. The
net flow of adsorbent towards the right
(net $C$) is 500 lbs./hr., the amount fed,
since there is no recirculation of solids.
Therefore the slope of the operating line

$$-\frac{\text{Net } S}{\text{Net } C} =$$

$$\frac{\text{solvent in wash} - \text{solvent entrained in cake}}{\text{Net } C}$$

$$= F - d \qquad (13)$$

It is now necessary to determine $-w$, the
slope of the underflow (filter cake) lines.

The washed filter cake carries solvent
from two sources. First it carries solvent
in the undisplaced solution from the pre-
ceding stage, and it also carries displacing
wash solvent obtained from the stage it is
entering. The displacing wash solvent is
not changing stages or its solute content,
so it obviously does not enter into the inter-
stage flows. Therefore the interstage flow
of solvent accompanying the filter cake
solids is the undisplaced solvent, or:

$$w =$$

$$\frac{\text{undisplaced solvent from preceding stage}}{\text{adsorbent in filter cake}}$$

Fig. 10. Constructions for countercurrent filtration problem.
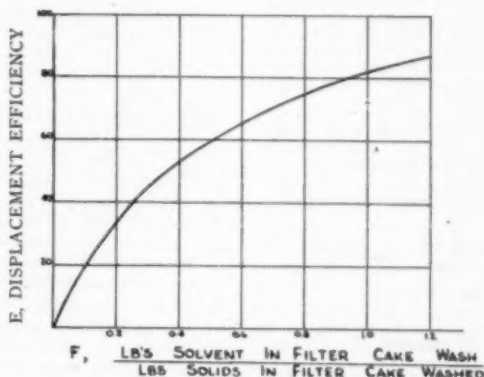
Fig. 11. Displacement efficiency of filter cake wash.

Therefore

$$w = \frac{(100 - E)}{100} d \qquad (14)$$

The filter cake dilution has been given in
the problem statement as 0.5, but the dis-
placement efficiency $E$ also must be known
before $w$, and hence the slope of the filter
cake lines, can be determined. Displace-
ment efficiency is known only as a function
of $F$ through Figure 11. The next step is
to determine $F$.
From Equation (13)

$$F = -\frac{\text{Net } S}{\text{Net } C} + d$$

But

$$\left(-\frac{\text{Net } S}{\text{Net } C}\right)$$

is the slope of the operating line. There-
fore if an operating line is drawn, the
ratio $F$ can be calculated. From Figure 11
the displacement efficiency can then be de-
termined, and finally $-w$, the slope of the
underflow lines can be calculated.

Perfected constructions are shown in
Figure 10. The procedure is to draw the
feed line, intercepting the axes as follows:

$$y_f' = \frac{6}{500} = 0.012$$

$$x_f' = \frac{6}{500} = 0.012$$

The extract line is drawn vertically above
the intercept

$$X_e' = 0.006$$

**Fig. 12. Countercurrent filtration.**

since the extract is to be saturated. The intersection of the feed and extract lines marks a point $Q$ on the operating line. The fresh solvent line is drawn as a vertical line above the intercept $X'_s = 0.001$.

A trial operating line is drawn through point $Q$. The slope of this trial operating line is determined and used with the known value of 0.5 for filter cake dilution to calculate the ratio $F$. Displacement efficiency is then determined from Figure 11. With this the value of $w$, and hence the slope of the underflow lines, is calculated. Stage constructions are made. If the underflow line from the second and final stage does not intersect the fresh solvent line at a point on the operating line, a new trial operating line is drawn and the stage construction procedure repeated.

From the slope of the correct operating line in Figure 10, the pounds net solvent per pound of solids is 0.45. The filter cake dilution was given as 0.5. Therefore the total pounds of solvent in the fresh solvent solution per pound of solids $= 0.45 + 0.50 = 0.95$ lbs. Thus $F = 0.95$.

Since $F = 0.95$, then from Figure 11, the value of $E$ is 80%. Therefore, from Equation (14), $w = 0.10$, which gives the negative slope of the filter cake lines. Neglecting small weight of solute contained, the amount of fresh solvent solution required

$$= 0.95 \frac{\text{lbs. solvent}}{\text{lbs. solids}} \times 500 \frac{\text{lbs. solids}}{\text{hr.}}$$

$$= 475 \text{ lbs./hr.}$$

## Summary

A graphical solution method potentially applicable to any steady state countercurrent transfer problem has been presented. The method is of theoretical interest as a general case relating the McCabe-Thiele and Ravenscroft methods. It should be useful in solving various leaching and solids extraction problems.

## Notation

The quantities of the constituents may be expressed in any units. They need not even be consistent among themselves. As an extreme example, $A$ might be expressed in terms of B.t.u., $C$ in terms of pounds plus kilocalories, and $S$ in terms of gram moles. The other variables are ratios among these three. In practice, however, it will avoid confusion if self-consistent units are used.

$A =$ quantity of a first constituent (distributed constituent) solvent

$A' =$ quantity of first constituent in overflow stream per unit time

$a' =$ quantity of first constituent in underflow stream per unit time

$A° =$ quantity of first constituent in light (overflow) phase

$a° =$ quantity of first constituent in heavy (underflow) phase

$C =$ quantity of a second constituent (carrier)

$C' =$ quantity of second constituent in overflow stream per unit time

$c' =$ quantity of second constituent in underflow stream per unit time

$C° =$ quantity of second constituent in light (overflow) phase

$c° =$ quantity of second constituent in heavy (underflow) phase

$d =$ filter cake dilution

$$= \frac{\text{lbs. solute-free solvent in filter cake}}{\text{lbs. solute-free solids in filter cake}}$$

$E =$ filter cake wash efficiency

$= $ per cent of solvent entrained in filter cake which comes from the displacing wash

$F =$ filter cake wash ratio

$$= \frac{\text{lbs. solvent in filter cake wash}}{\text{lbs. solute-free solids in filter cake}}$$

$M$ denotes final stage of battery or cascade

$N$ denotes any stage of battery or cascade

$S =$ quantity of a third constituent (second carrier, solvent)

$S' =$ quantity of third constituent in overflow stream per unit time

$s' =$ quantity of third constituent in underflow stream per unit time

$S° =$ quantity of third constituent in light (overflow) phase

$s° =$ quantity of third constituent in heavy (underflow) phase

$W = S/C$

$W' = S'/C'$, refers to overflow stream

$w' = s'/c'$, refers to underflow stream

$W° = S°/C°$, refers to overflow phase

$w° = s°/c°$, refers to underflow phase

$X = A/S$

$X' = A'/S'$, refers to overflow stream

$x' = a'/s'$, refers to underflow stream

$X° = A°/S°$, refers to overflow phase

$x° = a°/s°$, refers to underflow phase

$X^* =$ coordinate of point on equilibrium line

$Y = A/C$

$Y' = A'/C'$, refers to overflow stream

$y' = a'/c'$, refers to underflow stream

$Y° = A°/C°$, refers to overflow (light) phase

$y° = a°/c°$, refers to underflow (heavy) phase

$Y^* =$ coordinate of point on equilibrium line

SUBSCRIPTS:

$_e =$ extract, overflow from stage 1

$_f =$ feed, underflow stream into stage 1

$_r =$ raffinate, underflow from stage $M$

$_s =$ solvent, overflow stream into stage $M$

$_m =$ flows from final unit of cascade

$_n =$ flows from any unit of cascade

SUPERSCRIPTS:

$'$—marks properties of total streams

$°$—marks properties of phases

$^*$—marks coordinates of equilibrium curve

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# PRESSURE DROP THROUGH STACKED SPHERES

## EFFECT OF ORIENTATION

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**F**LOW of fluids through porous media is encountered often in chemical engineering. Estimation of pressure drop through these media is of considerable importance in many applications, and as a result, many investigations have been conducted on the flow of fluids through packed beds of particles of one sort or another. These investigations have led to a wide variety of pressure-drop correlations usually involving the density, viscosity, and velocity of the fluid, the diameter, shape, and roughness of the particles, and the porosity or void volume of the packed bed.

However, one factor which has occasionally raised some question as to its effect is the orientation of the particles. Since the packed beds usually studied are formed by random dumping, it is obvious that the effect of orientation has been more or less neglected. It has simply been assumed that if the same particles are randomly packed to the same bed porosity, orientation of the particles will be approximately the same on the average.

To clear up questions of the effect of orientation on pressure drop, it was decided to initiate a fundamental investigation of beds of definite geometrical arrangements of particles. A survey of the different shapes of particles suitable for such a study showed that spheres offer about as wide a variation in arrangement as can be obtained in any way with other shapes. For this reason beds of stacked spheres were selected for the study.

Before making any pressure-drop measurements, it was necessary to determine just what possible ways there were for stacking spheres. Fortunately, in 1935 Graton and Fraser (*3*) made a thorough study of the stacking of spheres, and it is largely their ideas which have been followed here.

Although there are an infinite number of ways to arrange spheres on a horizontal plane, there are two simple ar-

rangements. One of these has all the sphere centers lying at the corners of squares, while the other has the sphere centers at the apices of equilateral triangles. The first case is called a square layer and the second is referred to as a rhombic layer. In Figure 1 it is seen that the arrangement Nos. 1, 2, and 3 are composed of square layers, whereas Nos. 4, 5, and 6 are constructed of rhombic layers. Properties of the different arrangements are given in Table 1, where it is observed that those with the same name have the same porosity. For example, Orthorhombic No. 2 is composed of square layers and Orthorhombic No. 4 is built of rhombic layers, but both have a porosity or fractional free volume of 0.3954.

Alternative arrangements are possible in the cases of the No. 2's, the No. 5's, and the No. 6's. For example, there are two No. 2's, designated Clear Passage and Blocked Passage. In the clear passage arrangement the spheres in any one layer are placed squarely over the spheres in the second layer below the one in question. This results in small vertical passageways which are carried through the full depth of the bed completely unobstructed, which is the reason for the designation. On the other hand, when constructing any one layer, it is possible to place the spheres in the center between four spheres lying in the second layer below the one in question. This blocks off completely the

vertical passageway and accounts for the designation Blocked Passage. Such a variation in orientation of the layers does not change the porosity. It will be seen that the No. 6's offer the same possibilities as the No. 2's. The No. 5's are slightly different in that there are two different procedures of stacking which lead to the blocked passage arrangement, though in this work only one of them was studied.

Although it first appears that there are several different arrangements of the same porosity, it turns out that some arrangements of the same general name are really identical as far as the arrangement itself is concerned; what is different is the major axis of flow or observation. Thus, if one builds Rhombohedral No. 3 and observes it along the proper axis, it will prove to be the same as Rhombohedral No. 6 clear passage. In the same way Orthorhombic No. 2 clear passage, if viewed properly, will be identical to Orthorhombic No. 4. In these cases one might say that it is the anisotropic property of the arrangement which is being studied.

To construct the arrangements based on square layers, a square container was used, while a hexagonal container served to hold the arrangements involving rhombic layers. To eliminate the excess porosity normally encountered at the walls of the container, fractional spheres were employed. In the case of square layers half-spheres were used
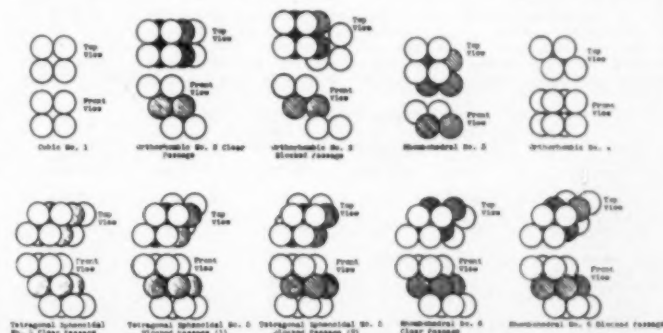


Fig. 1. Sphere arrangements based on square and rhombic layers.

| 2a<br>Cubic<br>No. 1 | 2b<br>Orthorhombic<br>No. 2 | 2c<br>Rhombohedral<br>No. 3 | 2d<br>Orthorhombic<br>No. 4 | 2e<br>Rhombohedral<br>No. 5<br>clear passage | 2f<br>Rhombohedral<br>No. 6<br>blocked passage |
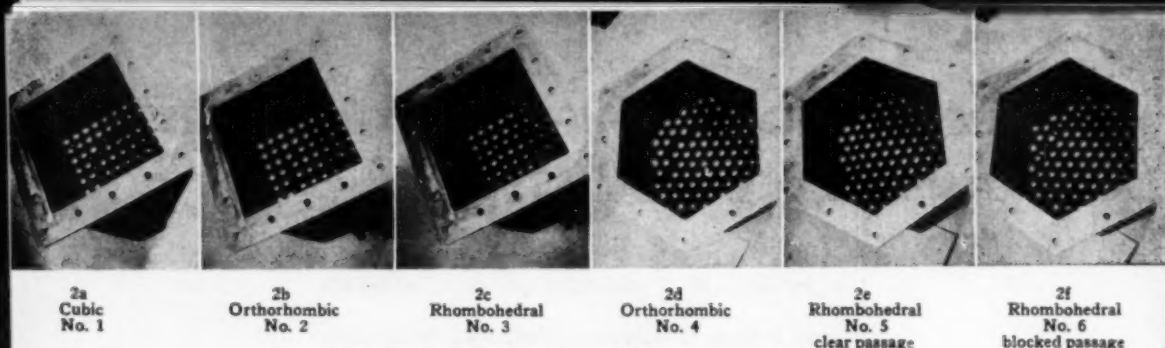
Fig. 2. Examples of different stacking arrangements using ¼-in. balls.

along the walls and quarter-spheres in the corners, while all but one of the rhombic arrangements utilized half- and one-third spheres. Figure 2 shows how these fractional spheres were employed in several arrangements. In the case of the No. 5 arrangements two rather odd fractions were required, being those produced by passing a plane through a sphere splitting a diameter perpendicular to that plane into one part ¾ and the other part ¼ the diameter long. Before deciding on the use of fractional spheres at the wall, calculations were made showing that more than 100 spheres would have been necessary across the container diameter to reduce the effect of wall porosity below the other errors which would occur in the measurements.

The stability of the different arrangements varied. As might be predicted, Cubic No. 1 proved to be exceedingly unstable and required extremely close tolerances on the container size and sphere diameter. Contrasted to the cubic, the rhombohedral arrangements are perfectly stable, which is to be expected as they cannot be condensed into tighter arrangements.

Two sizes of brass ball bearings were used as the packing material. These measured ⁵⁄₁₆ and ⅝ in. in diameter, and careful checking of the diameters with a micrometer showed only about one to two ten thousandths of an inch variation. The surface was smooth at the start and every effort was made to keep it that way so that surface roughness would not be a factor in controlling pressure drop. The ball bearings were packed in brass containers, two of which were square and one hexagonal in cross section. The square containers had inside edges measuring 5.00

in. and 2.50 in. respectively, while the internal cross section of the hexagonal container was circumscribed by a circle of radius 3.248 in. The containers were fitted with drilled support plates and baffle plates. Figure 3 shows the 5-in. square container in operating position. The spheres were packed in the bottom half between the two pressure taps. The top half contained the baffle plate and served as a short calming section. The two halves were bolted together with a neoprene gasket cut carefully to preserve as smooth an inside wall as possible.

The fluids used were Pittsburgh tap water and Gulf No. 381 hydraulic oil, and these were pumped downward through the bed so as not to upset the arrangements. Even with downward pumping and care in operating, occasionally a bed would shift (especially in the case of the unstable Cubic No. 1), in which case the data would be disregarded. The fluids were recirculated through a weigh-and-storage tank by means of a 3-hp. centrifugal pump. Flow rate was controlled by a weighted diaphragm valve and measured by a calibrated rotameter. Pressure drop across the bed and its support plate was measured with either an inverted 40-in. manometer using the fluid flowing or by a well-type 60-in. mercury manometer, as can be seen in Figure 3. Temperature of the fluid was measured so that the density and viscosity could be determined from plots of these properties versus temperature. Viscosities were determined in modified Cannon-Ostwald viscometer tubes suspended in a constant temperature bath. Densities were measured with a Fisher precision hydrometer.

For a pressure-drop test the container was packed with the desired arrangement of spheres and connected into the pumping system. Flow through the bed was started slowly and gradually increased to a maximum where it was maintained until all air bubbles were eliminated as noted in the rotameter. This was followed by careful draining of the manometer lines, after which the data could be taken whenever

equilibrium was reached for a given flow rate. In the case of water, equilibrium was established quickly after setting the flow rate; however, the oil often required considerable time (15 to 20 min.) to reach equilibrium.

Since the data for the water runs were taken at essentially one temperature or one viscosity and density, it was possible to construct a fairly simple plot to allow for entrance and exit effects. For any given arrangement the pressure drop was plotted against the superficial fluid velocity with the number of layers of spheres as the parameter. By a process of subtraction of pressure drops at the same velocity, it was possible to determine when the pressure drop per additional layer was uniform, which was the value ultimately sought. The oil runs were handled differently as the data for different numbers of layers were not always taken at the same temperature. The procedure used was to plot $\Delta H/V_e^2$ vs. $V_e\rho/\mu$ with the number of layers as the parameter. Here $\Delta H$ is the pressure drop, $V_e$ is the superficial fluid velocity, $\rho$ is the fluid density and $\mu$ is the fluid viscosity. By the subtraction process the $\Delta H/V_e^2$ per additional layer was determined and the uniform value which resulted was the one used in the calculations.

Dimensional analysis of the problem of pressure drop through porous media of considerable thickness leads to the expression

$$\frac{\Delta H g_c D p}{Z V_e^2} =$$

$$F\left(\frac{D_p V_e \rho}{\mu}, \epsilon, \frac{e}{D_p}, \frac{D_p}{D}, \phi, \beta\right) \quad (1)$$

where

$D_p$ is the particle diameter
$Z$ is the bed depth
$\epsilon$ is the fractional void volume
$e$ is a representative height of surface roughness
$\phi$ is the shape factor of the particle
$\beta$ is an orientation factor
$D$ is the diameter of the container
$g_c$ is the mass to force conversion factor

TABLE 1.—SOME DATA ON STACKING OF SPHERES

| Name of Stacking Arrangement | Distance Between Layers | Number of Tangent Neighbors | Porosity (fractional free volume) | Largest Fractional Free Area | Smallest Fractional Free Area |
|---|---|---|---|---|---|
| No. 1<br>Cubic | $D_p$ | 6 | 0.476 | 1.0 | 0.214 |
| No. 2<br>Orthorhombic | $0.866D_p$ | 8 | 0.3954 | 0.635 | 0.214 |
| No. 3<br>Rhombohedral | $0.707D_p$ | 12 | 0.2595 | 0.349 | 0.214 |
| No. 4<br>Orthorhombic | $D_p$ | 8 | 0.3954 | 1.0 | 0.093 |
| No. 5<br>Tetragonal Sphenoidal | $0.866D_p$ | 10 | 0.3019 | 0.590 | 0.093 |
| No. 6<br>Rhombohedral | $0.816D_p$ | 12 | 0.2595 | 0.455 | 0.093 |

The left side of this equation is usually called a 'friction factor. For the case of flow through a single arrangement of smooth spheres with negligible wall effect, the above function simplifies to the friction factor being a function of only the Reynolds number,

$$\frac{\Delta H g_c D_p}{Z V_o{}^2} = F'\left(\frac{D_p V_o \rho}{\mu}\right) \quad (2)$$

since the shape and roughness of the spheres and the orientation and porosity of the bed are fixed. This function, with the addition of a 2 in the denominator of the ordinate, has been plotted graphically in Figures 4 and 5. Figure 4 shows the data points as they were obtained for Orthorhombic No. 2. Corresponding graphs were determined for all the other arrangements, but are not presented here. In Figure 5 the curves from Figure 4 and the corresponding plots just referred to have been reproduced without the interference of the many data points.

Results of this study are compared with the work of Carman (2). Using the data of many investigators, Carman plotted $\Delta H g_c \epsilon^3 / Z V_o{}^2 a$ vs. $\rho V_o / \mu a$ and obtained a single smooth curve for random packings of spheres. Here $a$ is the surface area of particles per unit volume of bed. For beds of spheres there is a simple relationship between the surface area and the porosity given by

$$a = \frac{6(1-\epsilon)}{D_p} \quad (3)$$

Applying this to the functions plotted by Carman, one obtains

$$\frac{\Delta H g_c D_p}{2Z V_o{}^2} = \left[\frac{3(1-\epsilon)}{\epsilon^3}\right]\left(\frac{\Delta H g_c \epsilon^3}{Z V_o{}^2 a}\right) \quad (4)$$

and

$$\frac{D_p V_o \rho}{\mu} = [6(1-\epsilon)]\left(\frac{\rho V_o}{\mu a}\right) \quad (5)$$

Thus, it was only necessary to read off the points from Carman's curve and multiply by the bracketed porosity correction factors to obtain the functions for Figure 5. This results in a series of curves on the type of plot used here —one for each different porosity. These are shown as dashed lines in Figure 5 and are to be compared with the curves of the different sphere stackings of the same porosity. The greatest differences occur with the Orthorhombic No. 4 and Cubic No. 1, where the measured pressure drops and those of random packing differ by several fold. Cubic No. 1 is also interesting for its increase of friction factor with Reynolds number at high velocities, for single spheres in moving fluids exhibit the same characteristic.

Attempts to correlate the results for all arrangements of spheres over all ranges of Reynolds number have not yet been successful. In streamline flow, however, the problem is somewhat simplified since the friction-factor curves are straight lines with a slope of −1 (i.e., on logarithmic coordinates) and since the curves for the different No. 2's, the different No. 5's, and the different No. 6's including the No. 3 come together in the streamline range. Therefore, in streamline flow there are only five different straight-line curves to be considered.

The first attempt to correlate all the streamline data was based on the application of the Navier-Stokes hydrodynamical equations. However, the boundary conditions on the resulting partial differential equations are complicated and so far no solution has been obtained. A semiempirical correlation, however, has been developed to predict the results with an average precision of 10 per cent. The development follows some of the ideas of Blake (1) and Kozeny (4).
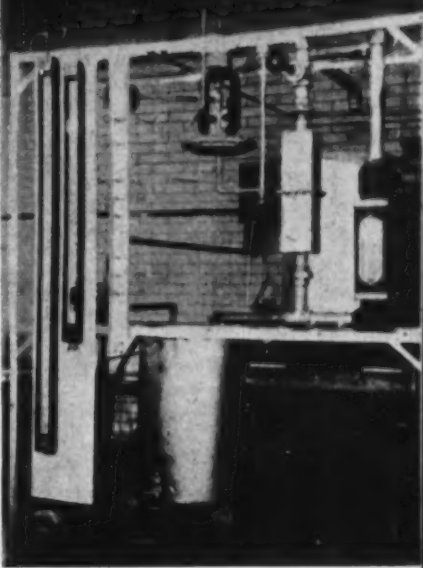


Fig. 3. Equipment stand with 5-in. square container in place.
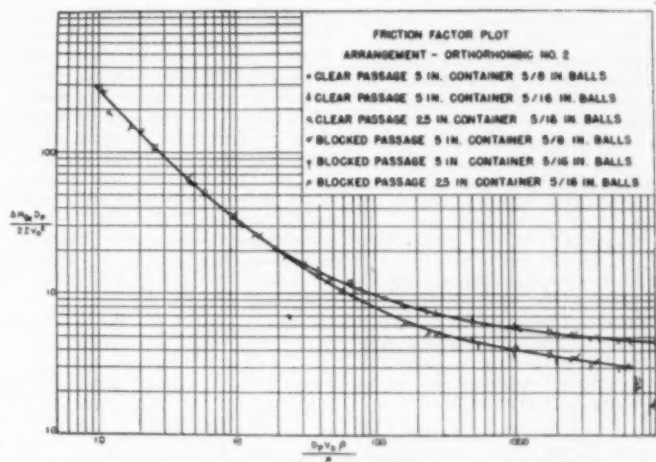


Fig. 4. Friction factor plot from original data for one arrangement—Orthorhombic No. 2.

TABLE 2.—COMPARISON OF STREAMLINE CORRELATION WITH EXPERIMENTAL DATA

Equation X. $\dfrac{\rho \Delta H g_o D_p{}^2}{22 V_o \mu Z} = \left(\dfrac{1}{h}\right)\displaystyle\int_0^h \dfrac{b^4(1-\epsilon)^2}{\epsilon^3}\, dZ$

$\left(\dfrac{1}{h}\right)\displaystyle\int_0^h \dfrac{b^4(1-\epsilon)^2}{\epsilon^3}\, dZ$

| Arrangement | Calculated from Geometry of Arrangement | $\dfrac{\rho \Delta H g_o D_p{}^2}{22 V_o \mu Z}$ Taken from Friction Factor Curves Through Data Points |
|---|---|---|
| Cubic No. 1 | 16.6 | 18.2 |
| Orthorhombic No. 2 | 20.7 | 24.8 |
| Rhombohedral No. 3 | 264. | 241. |
| Orthorhombic No. 4 | 179. | 166. |
| Tetragonal sphenoidal No. 5 | 210. | 190. |
| Rhombohedral No. 6 | 298. | 241. |

FRICTION FACTOR PLOT

| | | |
|---|---|---|
| 1-1 | CUBIC NO. 1 | ϵ 0.476 |
| 2-2' | ORTHORHOMBIC NO. 2 CLEAR PASSAGE | ϵ=0.3954 |
| 2-2 | ORTHORHOMBIC NO. 2 BLOCKED PASSAGE | ϵ=0.3954 |
| 4-4 | ORTHORHOMBIC NO. 4 | ϵ=0.3994 |
| 5-5 | TETRAGONAL SPHENOIDAL NO. 5 CLEAR PASSAGE | ϵ 0.3019 |
| 5-5' | TETRAGONAL SPHENOIDAL NO. 5 BLOCKED PASSAGE | ϵ=0.3019 |
| 6-6 | RHOMBOHEDRAL NO. 6 BLOCKED PASSAGE | ϵ=0.2595 |
| 6-3 | RHOMBOHEDRAL NO. 3 | ϵ=0.2595 |
| 6-6' | RHOMBOHEDRAL NO. 6 CLEAR PASSAGE | ϵ=0.2595 |

DASHED CURVES FROM CARMAN'S (2) CORRELATION

A-A ϵ=0.476
B-B ϵ=0.3954
C-C ϵ=0.3019
D-D ϵ=0.2595

Fig. 5. Smoothed friction factor curves for all arrangements compared with Carman's (2) correlation.

Consider flow through a porous bed to be analogous to flow through a bundle of parallel pipes and apply Poiseuille's law,

$$\rho \Delta H = \frac{KVZ\mu}{g_c D^2} \qquad (6)$$

where $V$ is the velocity through pipes of diameter $D$ and $K$ is a constant. In terms of the superficial velocity, $V$ may be approximated by $V_o/\epsilon$; also the pipe or average channel diameter in a packed bed may be approximated as $D = \epsilon/a$. Recalling the relation given above involving $a$, $\epsilon$, and $D_p$, one may obtain

$$\rho \Delta H = \frac{K'V_o\mu(1-\epsilon)^2 Z}{g_c D_p^2 \epsilon^3} \qquad (7)$$

In the case of stacked spheres $\epsilon$ may be thought of as the fractional free area of infinitesimal bed depth $dZ$, as well as the fractional void volume over a finite height. Therefore, since the fractional free area varies through the bed, it may be treated as a function of $Z$, or

$$\rho \Delta H = \frac{K'V_o\mu}{g_c D_p^2} \int_0^Z \frac{(1-\epsilon)^2}{\epsilon^3} dZ \qquad (8)$$

The change of fractional free area will be periodic from layer to layer; therefore, one may write

$$\rho \Delta H = \frac{K'V_o\mu Z}{g_c D_p^2} \left(\frac{1}{h}\right) \int_0^h \frac{(1-\epsilon)^2}{\epsilon^3} dZ \qquad (9)$$

where $h$ is the height of the periodic change in the arrangement in question. The expression

$$(1/h) \int_0^h \frac{(1-\epsilon)^2}{\epsilon^3} dZ$$

is then a property of the given arrangement.

Equation (9) still does not correlate the data, for it has been found necessary to introduce an empirical term $b^4$ under the integral sign; where $b$ has a value of one so long as a horizontal plane passed through the bed of spheres cuts the minimum number of spheres, and a value of two when the horizontal plane cuts twice the minimum which occurs at those points where the plane cuts the spheres from two different layers. When the term $b^4$ is inserted, and the constant $K'$ evaluated from the experimental results, the following equation is evolved:

$$\rho \Delta H = \frac{22V_o\mu Z}{g_c D_p^2} \left(\frac{1}{h}\right) \int_0^h \frac{b^4(1-\epsilon)^2}{\epsilon^3} dZ \qquad (10)$$

Values of

$$\left(\frac{1}{h}\right) \int_0^h \frac{b^4(1-\epsilon)^2}{\epsilon^3} dZ$$

were calculated from the geometry of each arrangement of spheres. Table 2 shows how well the proposed equation represents the experimental data.

In summarizing, orientation has been shown to have a definite effect on pressure drop through stacked spheres. It seems reasonable then that orientation differences can account for the variation in pressure drop through beds of particles of the same diameter and shape packed to the same porosity. Such differences will be expected to be greatest when comparing packings where orientation can be preferred or directed, such

as stacked Raschig rings and dumped Raschig rings. For these a single porosity correlation might be seriously in error.

### Notation

(With representative units)

$a$ = surface area of particles per unit volume of bed, sq.ft./cu.ft.

$b$ = term introduced in streamline flow equation. Has a value of one when a plane passed through the bed perpendicular to the major flow axis cuts spheres from only one layer, and a value of two when spheres from two layers are cut by the plane

$D$ = diameter of column or packing container, ft.

$D_p$ = diameter of particles or packing units, ft.

$e$ = height of protrusions or valleys contributing to surface roughness of particle, ft.

$F, F'$ = symbols for algebraic functions

$g_c$ = conversion factor from mass to weight units, 32.2 (lb. mass)(ft.)/(lb. force)(sec.) (sec.)

$\Delta H$ = pressure drop in height of flowing fluid, ft. (more specifically, ft. lb. force/lb. mass)

$h$ = height of periodic variation in stacked spheres, ft.

$K, K'$ = constants in equations

$V$ = linear velocity at a point, ft./sec.

$V_o$ = superficial velocity based on empty column, ft./sec.

$Z$ = height of packed column, ft.

$\beta$ = orientation factor

$\epsilon$ = porosity or fractional free volume of a packed bed. For a bed of infinitesimal height, it is the fractional free area

$\mu$ = viscosity, lb. mass/(ft.)(sec.)

$\rho$ = density, lb. mass/cu.ft.

$\phi$ = shape factor of a particle

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(Presented at Boston Meeting, Boston, Mass.)

# MOVING BED RECYCLE CATALYTIC CRACKING CORRELATIONS

## Product Distribution and Process Variables

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THIS paper presents the results of a pilot plant investigation of moving bed recycle catalytic cracking of petroleum fractions to determine the effect of the process variable recycle ratio on product yields and quality. A previous paper (1) presented a correlation showing the effect of the process variables of space rate, catalyst-to-oil ratio and temperature for once-through catalytic cracking. An extension of this investigation to include the effect of an additional process variable, recycle ratio, is presented herein. Together these two papers provide methods for estimating product yields over the full range of operating conditions normally employed in commercial cracking units.

In recycle cracking operations the total reactor effluent boiling above gasoline is fractionated into a light gas oil cut, a heavy gas oil cut, and a polymer bottoms. In this investigation, the heavy gas oil was used as recycle and

was charged to the reactor along with the fresh feed. The polymer bottoms yield was arbitrarily set at 5 wt. % of fresh feed for all runs. The ratio of the quantity of recycle to the quantity of fresh feed is defined as recycle ratio. Once-through operation is therefore the lower limit of recycle operation, i.e., operation at zero recycle ratio. As recycle ratio is increased at constant fresh feed rate, progressively larger amounts of heavy gas oil are returned to the reactor. By cracking the heavy gas oil to extinction in recycle opera-

tion, a higher yield of gasoline from a given fresh feed can be obtained. A detailed knowledge of the effect of recycle operation on the process results is necessary for the most efficient design and operation of commercial cracking units.

### Presentation of Data

Cracking results reported herein were obtained from a moving bed pilot unit which has a maximum charge capacity of approximately 3 bbl./day. The charge stock used in this study was an

### TABLE A

| | |
|---|---|
| Gravity, ° API | 28.9 |
| Vacuum Distillation, ° F. (corrected to 760 mm. Hg.) | |
| 10% | 652 |
| 50% | 746 |
| 90% | 889 |
| End Point | 928 |
| Sulfur, wt. % | 0.38 |
| Aniline Point, ° F. | 192 |

### TABLE B

| | |
|---|---|
| Recycle Ratio | 0.5, 1.0, 2.0 |
| Cracking Temperature, ° F. | 850, 900, 950 |
| Space Rate, wt./(hr.)(wt.) | 0.9-5.0 |

NOTE: Additional data concerning charge stock inspections; pilot plant data which include operating conditions, yields, and product inspections for the operations conducted at cracking temperatures of 850°, 900°, and 950° F. respectively are on file (Document 3128) with the American Documentation Institute, 1719 N Street, Northwest, Washington, D. C. Obtainable by submitting $1.00 for microfilm and $1.80 for photocopies.
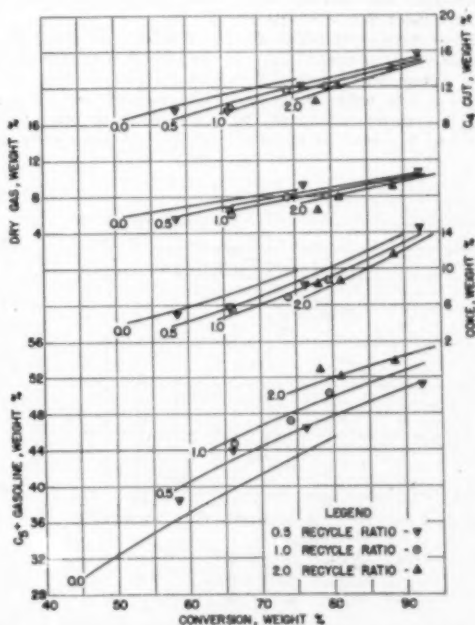


Fig. 1. Product distribution vs. conversion at 850° F.
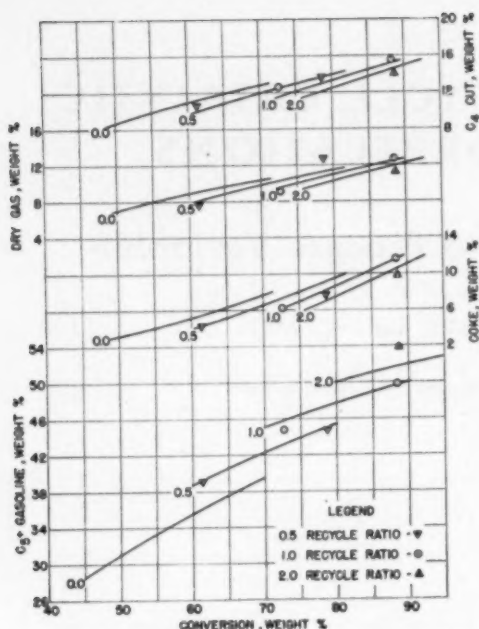
Fig. 2. Product distribution vs. conversion at 900° F.
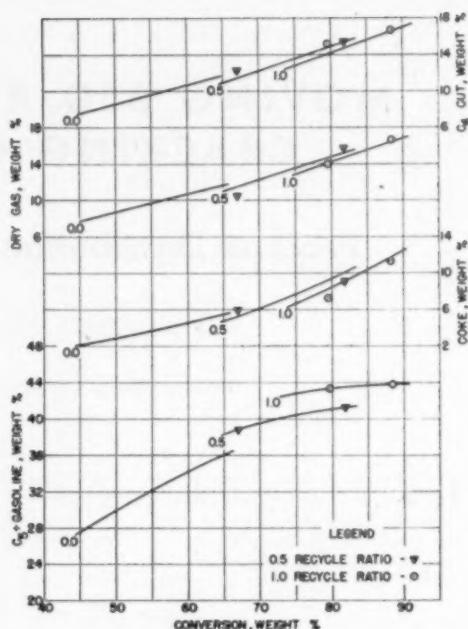


Fig. 3. Product distribution vs. conversion at 950° F.

East Texas heavy gas oil (56-77 vol. % of crude) whose properties are summarized in Table A. Only one catalyst, a 33 A.I. plant-aged silica-alumina bead, was used throughout this investigation.

Experimental data upon which this paper is based were obtained from a series of 19 recycle cracking runs. Recycle ratio, cracking temperature, and space rate were varied individually to cover the range of operations tabulated in Table B. Catalyst-to-oil weight ratio was held constant at 2.15 throughout this investigation with the exception of one run where it was increased to 6.6.

*Product Distribution.* Conversion may be used to indicate the extent of the cracking reaction and is defined as 100 minus the per cent of catalytic gas oil based on the fresh feed charge. The weight per cent conversion may be de-

fined also as the sum of the weight per cent yields of gasoline and lighter products plus coke.

Product yields obtained at cracking temperatures of 850° F., 900° F., and 950° F. are presented as a function of conversion in Figures 1-3, respectively. Recycle ratios are shown as parameters on each graph. The curves drawn for zero recycle ratio were obtained from data and correlations previously pub-
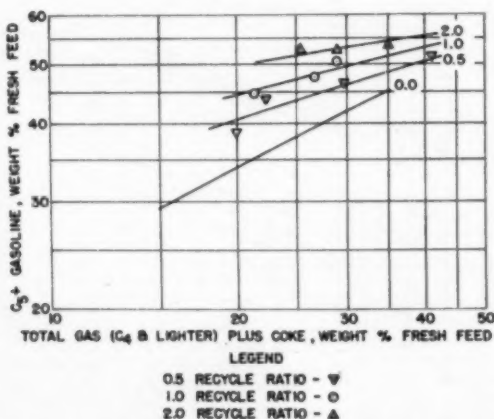


Fig. 4. Relationship between yields of total gas (C₄ and Lighter) plus coke and gasoline at 850° F.
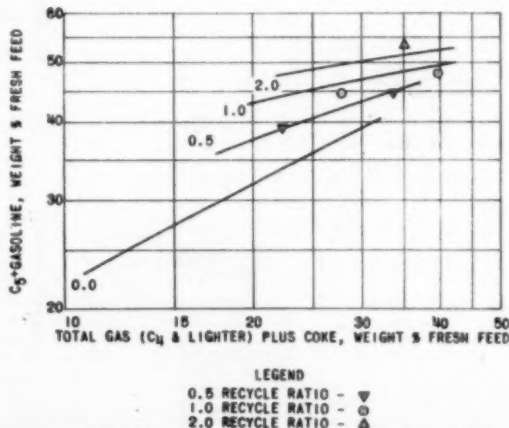


Fig. 5. Relationship between yields of total gas (C₄ and Lighter) plus coke and gasoline at 900° F.
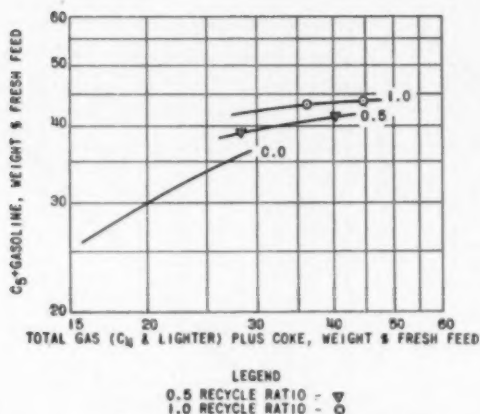
Fig. 6. Relationship between yields of total gas (C₄ and lighter) plus coke and gasoline at 950° F.

LEGEND
0.5 RECYCLE RATIO - ▽
1.0 RECYCLE RATIO - ○



Fig. 7. Relationship between yields of total gas (C₄ and lighter) and coke.

LEGEND

| CRACKING TEMPERATURE | 850°F. | 900°F. | 950°F. |
|---|---|---|---|
| 0.5 RECYCLE RATIO - | ▼ | ▽ | ▷ |
| 1.0 RECYCLE RATIO - | ○ | ⊘ | ⊘ |
| 2.0 RECYCLE RATIO - | ▲ | ◁ | |

**TABLE 1**

| Temperature, °F. | 850 | | | 900 | | | 950 | |
|---|---|---|---|---|---|---|---|---|
| Recycle Ratio .............. | 0.5 | 1.0 | 2.0 | 0.5 | 1.0 | 2.0 | 0.5 | 1.0 |
| Octane Numbers | | | | | | | | |
| F-2 Clear ............... | 79.9 | 80.3 | 79.8 | 80.8 | 80.9 | 81.0 | 80.8 | 81.3 |
| F-2 + 3cc. TEL ......... | 86.9 | 86.0 | 86.0 | 86.2 | 86.5 | 86.6 | 85.8 | 86.9 |
| F-1 Clear ............... | 90.4 | 90.6 | 90.3 | 93.0 | 92.5 | 92.9 | 94.8 | 94.3 |
| F-1 + 3cc. TEL ......... | 97.5 | 97.4 | 96.8 | 99.6 | 98.3 | 98.8 | 98.8 | 98.7 |

**TABLE 2**

| | | | |
|---|---|---|---|
| Conversion, vol. % ................................... | 60 | 70 | 80 |
| Gas Oil Yield, vol. % ................................. | 35 | 25 | 15 |
| Gravity, ° API ...................................... | 26.6 | 24.4 | 20.4 |
| Aniline Point, ° F. .................................. | 180 | 115 | 39 |
| ASTM Distillation, ° F. | | | |
| 10% evap. ...................................... | 543 | 525 | 474 |
| 50% evap. ...................................... | 598 | 562 | 484 |
| 90% evap. ...................................... | 657 | 615 | 508 |

lished (1). The curves which represent the recycle data are consistent with correlations presented in a subsequent section of this paper.

At constant recycle ratio and temperature, the yields of gasoline, C₄ cut, dry gas, and coke increase with an increase in conversion. At constant conversion, gasoline yield increases and the yields of coke, dry gas, and C₄ cut decrease with an increase in recycle ratio at each temperature level. At constant conver-



LEGEND

| CRACKING TEMPERATURE | 850°F. | 900°F. | 950°F. |
|---|---|---|---|
| 0.5 RECYCLE RATIO - | ▼ | ▽ | ▽ |
| 1.0 RECYCLE RATIO - | ○ | ⊘ | ○ |
| 2.0 RECYCLE RATIO - | ▲ | ◁ | |

Fig. 8. Relationship between yields of total gas (C₄ and lighter) and dry gas.



LEGEND

| CRACKING TEMPERATURE | 850°F. | 900°F. | 950°F. |
|---|---|---|---|
| 0.5 RECYCLE RATIO - | ▼ | ▽ | ▽ |
| 1.0 RECYCLE RATIO - | ○ | ⊘ | ○ |
| 2.0 RECYCLE RATIO - | ▲ | ◁ | |
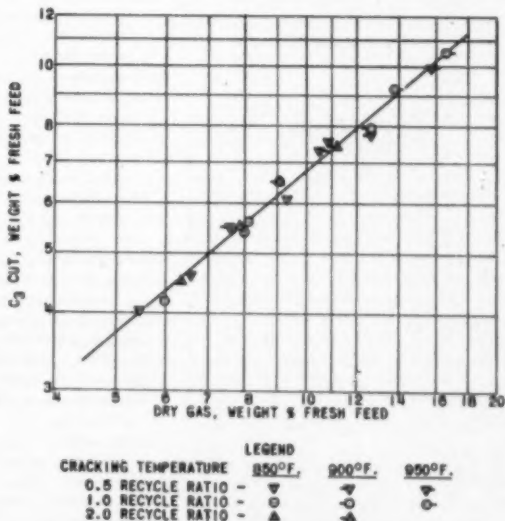
Fig. 9. Relationship between yields of dry gas and C₃ cut.

Fig. 10. Weight % $C_5$ + gasoline vs. volume % $C_5$ + gasoline.



Fig. 11. Weight % yield of total gas oil vs. volume % yield of total gas oil.

sion and recycle ratio, the yields of gasoline and coke decrease and the yields of $C_4$ cut and dry gas increase with an increase in cracking temperature.

It has been shown previously that space rate and catalyst-to-oil ratio are interchangeable variables in once-through cracking (1). In this study one run at 850° F. cracking temperature, 0.5 recycle ratio, and 92.3 wt. % con-

version was made at the higher catalyst-to-oil ratio of 6.6. The product distribution obtained on this run is consistent with those obtained at 2.15 catalyst-to-oil weight ratio. This indicates that space rate and catalyst-to-oil ratio are also interchangeable variables in recycle cracking.

*Product Quality.* The most important quality factor of the gasoline is its octane number. At constant cracking temperature, recycle ratio has no effect on octane number. This is shown in Table 1 by the average octane rating obtained at each recycle ratio and temperature.

The gas oil product is that portion of the synthetic crude which boils between gasoline and cycle stock. The important properties of this material are its boiling range, gravity, and aniline point. General trends which depict the effect of conversion on the gravity, aniline point, and boiling range of the light gas oil are shown in Table 2.

API gravity and aniline point of the gas oil decrease with an increase in conversion and are independent of recycle ratio and cracking temperature. The marked decrease in the 90% evaporated point with an increase in conversion shows that the increased conversion is obtained by cracking the heavy portion of the light gas oil. Recycle ratio has no discernible influence on the boiling range except as it affects

conversion. Temperature appears to have some independent effect on the boiling range of the light gas oil, but insufficient data are available to establish this effect quantitatively. In general, at constant conversion the higher temperatures produce somewhat higher boiling gas oils.

## Correlation of Experimental Data

It was demonstrated in the once-through moving bed cracking studies that the yield data could be correlated on the basis of relationships which were found to exist among the yields of the products from the cracking reaction. It was shown also that the effect of the process variables on product yields could best be correlated with the yield of total gas plus coke (1). Correlation of the data from the recycle operations has followed this same general plan.

*Interrelationships of Products of Cracking.* Figures 4-6 present the relationship between the yield of $C_5$+ gasoline and the yield of total gas plus coke at temperatures of 850° F., 900° F., and 950° F., respectively. Parameters of recycle ratio are indicated on these figures. At constant temperature and constant yield of total gas plus coke, gasoline yield increases with an increase in recycle ratio. At constant temperature and recycle ratio, gasoline yield increases with an increase in yield of total gas plus coke. When recycle ratio is held constant, the gasoline yield decreases with an increase in cracking temperature at a constant yield of total gas plus coke. Figures 4-6 also may
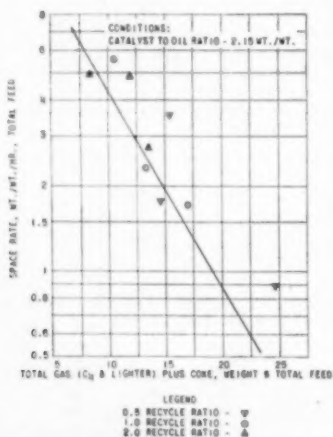


Fig. 12. Effect of space rate on yield of total gas plus coke at 850° F.

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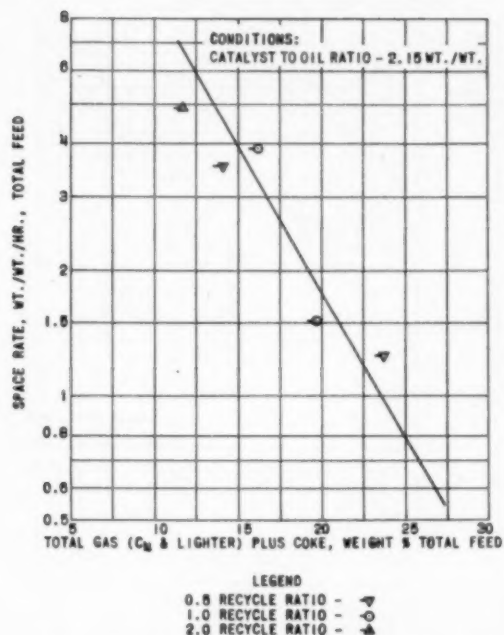
Fig. 13. Effect of space rate on yield of total gas plus coke at 900° F.
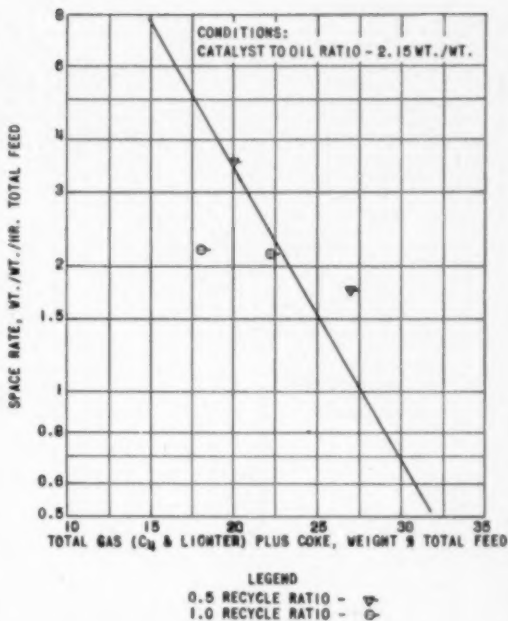
Fig. 14. Effect of space rate on yield of total gas plus coke at 950° F.

be used to determine the yield of gas oil since the difference between 100 and the sum of the weight per cent yields of gas plus coke and gasoline is equivalent to the weight per cent yield of gas oil.

The relationship between the yields of total gas ($C_4$ and lighter product) and coke is shown in Figure 7. The temperature parameters shown are those obtained in the correlation of once-through cracking data. These parameters define the recycle cracking results within the accuracy of the data. Recycle ratio has no effect on the relationship between the yields of total gas and coke. This relationship shows that the total gas yield increases with an increase in coke yield at any given temperature and also increases at constant coke yield with an increase in cracking temperature.

The relationship between the yields of total gas ($C_4$ and lighter) and dry gas ($C_3$ and lighter) is shown in Figure 8 to be a linear function on logarithmic coordinates at constant cracking temperature. Recycle ratio has no effect on this relationship. The temperature parameters used to represent the recycle data were those obtained from the once-through data although the recycle results indicate there might be a slightly different slope for these parameters.

The dry gas yield increases with an increase in total gas yield at any cracking temperature and also increases with an increase in cracking temperature at a constant total gas yield. The yield of $C_4$ cut can be obtained by the difference between the yield of total gas and dry gas.

Figure 9 shows the relationship between the yield of dry gas ($C_3$ and lighter) and the yield of total $C_3$ cut. This relationship is independent of recycle ratio and temperature. The yield of $C_3$ cut increases with an increase in dry gas yield. The yield of $C_2$ and lighter product can be obtained by difference between the yields of dry gas and total $C_3$ cut.

Since the yields of gasoline and gas oil are normally presented on a volume basis, it is necessary to have available a method for converting the weight per cent yields presented in the preceding correlations to a volumetric basis. Figure 10 presents the relationship between the weight and volume per cent yields of gasoline. Figure 11 presents the relationship between the weight and volume per cent yields of total gas oil.

*Effect of Process Variables on Product Distribution.* The preceding correlations have established the interrelationships among the yields of the var-

ious products of the cracking reaction. Such correlations are insufficient in themselves for process design work since they do not relate product distribution to operating conditions. Therefore, the experimental data were analyzed to determine the effect of space rate, catalyst-to-oil ratio, cracking temperature, and recycle ratio on product distribution.

It was found that if space rate, catalyst-to-oil ratio, and the yield of total gas plus coke were calculated on a total feed basis (fresh feed plus recycle stock), all recycle data fell, within experimental error, on lines predicted from the correlation of process variables already established for once-through cracking (1). This is illustrated for cracking temperatures of 850° F., 900° F., and 950° F. in Figures 12-14. At a constant temperature and a catalyst-to-oil weight ratio of 2.15, the yield of total gas plus coke, based on the total reactor feed, varies inversely with the log of the total space rate. Recycle ratio appears to have no effect on this relationship.

No separate investigation was made to determine the effect of catalyst-to-oil ratio on the yield of total gas plus coke in recycle operation. However, one recycle run was made at a catalyst-to-oil weight ratio of 6.6. The yield of total
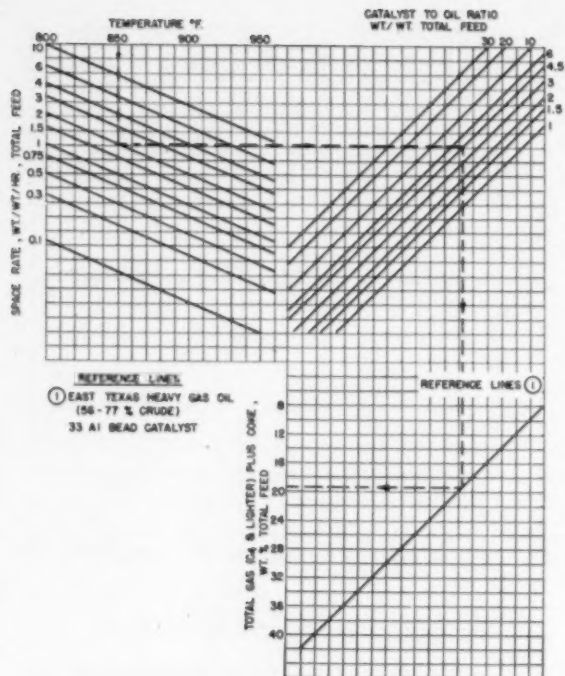
Fig. 15. Effect of process variables on yield of total gas plus coke.



Fig. 16. Relationship between yields of total gas plus coke and C₅ + gasoline.
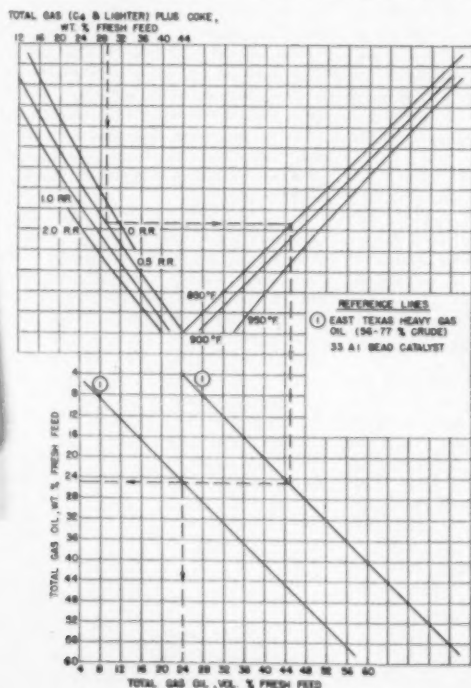


Fig. 17. Relationship between yields of total gas plus coke and total gas oil.
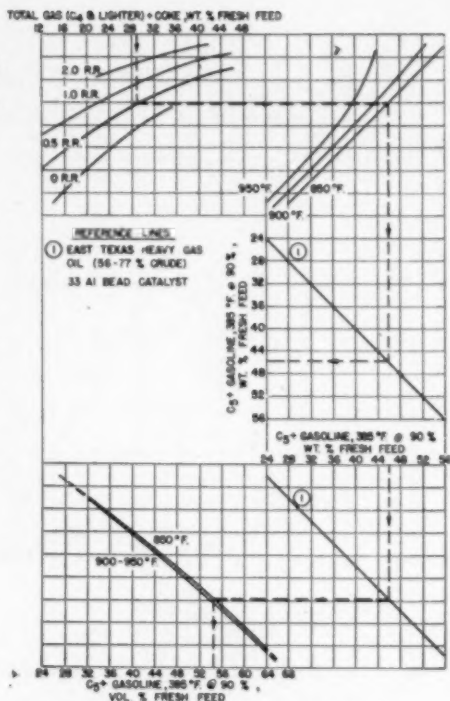
gas plus coke from this run was 26.6 wt. % based on total feed compared with 26.7 wt. % predicted from the correlation of once-through cracking data. It has been assumed therefore that the relationships between the process variables and the yield of total gas plus coke which were developed from once-through cracking data would also apply to the recycle cracking data when space rate, catalyst-to-oil ratio, and the yield of total gas plus coke are calculated on a total feed weight basis.

## Applications of Correlations

The correlations developed in the preceding section make it possible to (1) predict the product distribution at a given temperature and recycle ratio when the yield of one major product is known, (2) predict the product distribution at a given set of operating conditions, and (3) predict the operating conditions necessary at a given temperature and recycle ratio to obtain a specific yield of one of the major products. These predictions become tedious when using the basic correlations in the form in which they were presented in Figures 4-14. Furthermore, a larger number of pilot plant runs would be necessary to establish the cracking characteristics of
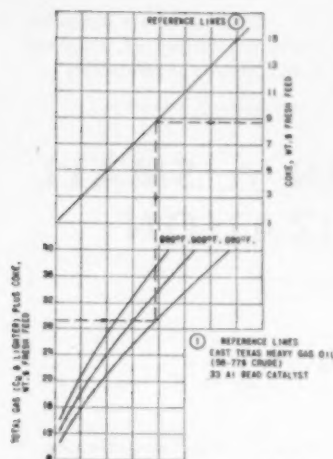
Fig. 18. Relationship between yields of total gas plus coke and coke.



Fig. 19. Relationship between yields of total gas and total C₄ cut.



Fig. 20. Relationship between yields of dry gas and total C₂ cut.

other types of stock and/or catalysts using the correlations in the aforementioned form. Therefore, the correlations have been made more functional by the construction of combination charts based on the relationships shown in the preceding section. These combination charts are presented in Figures 15-20. The reference lines shown are for cracking East Texas heavy gas oil (56-77% of crude) over 33 A.I. silica-alumina bead catalyst. The guide lines illustrate an example in which product distribution is predicted for a given set of operating conditions. It should be

noted that the yield of gas plus coke obtained from Figure 15 is based on the total feed. This must be converted to a fresh feed basis by multiplying by the term (one plus recycle weight ratio) before it can be used on Figures 16-18, inclusive.

The validity of the correlations and combination charts has been checked using different types of charge stocks and catalysts. The combination charts can be adapted to all normal cracking catalysts and to all charge stocks which are essentially free of nitrogen (less than 0.1 wt. % N).

The combination charts are easily adapted to other types of charge stocks and/or catalysts by means of appropriate reference lines. The basic cracking characteristics of a given charge stock and/or catalyst can be obtained with a minimum number (3-5) of properly chosen pilot plant runs. Experimental data thus obtained can be plotted on the various combination charts to establish the appropriate reference lines.

## Conclusions

By means of the correlations developed, it is possible (1) to predict the product distribution at a given recycle ratio and temperature when the yield of one major product is known, (2) predict the product distribution at a given set of operating conditions, and (3) predict the operating conditions necessary at a given temperature and recycle ratio to obtain a specified yield of one of the

major products. The correlations can be adapted to other charge stocks (essentially free of nitrogen) and/or catalysts by establishing reference lines on the combination charts with a minimum of three sets of experimental data. These correlations will not only assist the process engineer in the design of commercial units, but also will provide a basis for adjusting the operation of commercial units to meet the individual refiner's requirements.

### Literature Cited

1. Schall, J. W., Dart, J. C., and Kirkbride, C. G., *Chem. Eng. Progress*, **45**, No. 12, 746 (1949).

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## ERRATA

In "Turbulent Diffusion in Fixed Beds of Packed Solids," by R. A. Bernard and R. H. Wilhelm (C.E.P. **46**, 233, 1950) the sign of the exponential in Equation (13) is reversed. The proper form of the equation is as follows:

$$C/C_A = a' \sum_{0}^{\infty} \frac{e^{[a-(a^2+4\beta_n)^{1/2}]z/2}}{(a^2+4\beta_n^2)^{1/2}} \cdot \frac{J_o(\beta_n r)}{J_o^2(\beta_n a)} \qquad (13)$$

Also the line following Equation (9) should read: "with $J_1(\beta_n a) = o. (\beta_o a)$, $(\beta_1 a)$, $(\beta_2 a)$ . . . are," etc.

*Here is another article for Management on how development is handled . . . this time by an executive of Canadian Industries, Limited, who in a brief but inclusive description, traces the history of a typical case . . . tells the who, what, where, and when of responsibility for estimates on costs and practicability. . . .*

# CHEMICAL ENGINEERING IN A SMALL DEVELOPMENT ORGANIZATION

### F. S. McCARTHY

### Canadian Industries Limited, Montreal, Canada

THE chemicals department of Canadian Industries Limited manufactures and sells a large number of industrial chemicals; it has plants in five places in eastern Canada, and sales offices all across the country. The department is made up of four divisions: production, sales, control, and development. The functions of the control division may not be as evident as those of the production and sales divisions; the term "control" has a much pleasanter association for chemical engineers than the nasty word "accounting." Development may not be so nasty a word but it is used in so many ways that it has come to have almost no meaning. The development division is mainly responsible for the growth of the department—either by expansion of existing production or through the manufacture of additional chemicals—and for the discovery and investigation of improvements to existing products and processes. It may be said that the future profits of the department depend to a high degree on this division. It employs about 25 people and has an annual budget, exclusive of research and pilot plant expenditures, of about $150,000.

The development division comprises three sections: pioneering, market research and chemical engineering. In principle the pioneering section is responsible for prosecuting the work of the division and the other sections provide the more specialized services of market research and chemical engineering and although this principle is usually applied, in practice it is sometimes more effective or more efficient to assign studies directly to one of the service sections.

This article will describe the functions and organization of the chemical engineering section, and explain by an example, how it works within the organization just outlined. Before doing this, however, two other departments of

the company must be mentioned. The chemicals department is only one of five industrial departments in the company and some of the more specialized functions common to all five groups, such as purchasing, research and engineering, have been organized into company departments serving all the industrial departments. In the development division the pioneering section is responsible for liaison with the company's research department and the chemical engineering section has close relations with the engineering department. The research department has a broad company responsibility but from the narrow development division viewpoint it is a place where research required by the division can be carried out under the guidance of the pioneering section. In general, the engineering department has a responsibility for all engineering carried out in the company but from the specialized point of view of the chemical engineering section it provides mechanical design and layout of process equipment, the buildings to house the equipment and the services to run it all on the basis of primary information supplied by the chemical engineering section. In addition, all capital estimates used in appropriation requests must be approved by the engineering department.

The chemical engineering section is concerned with the physical means of production—the actual pumps, pipes, heat exchangers and other equipment used for manufacture and, since economic plant design is the compromise between capital and operating costs resulting in minimum over-all production cost, the chemical engineering section is also responsible for establishing the number and caliber of operating and maintenance people and the preparation of operating instructions. From this general definition it follows that the principal duties of the section are:

Selection, design and specification of process equipment
Tabulation of service requirements (steam, electricity, etc.)
Determination of operating crew size
Operating cost estimates
Preliminary capital estimates
Pilot plant design and operation
Liaison with engineering department
Start-up of full-scale plant

The organization of the chemical engineering section is shown in Figure 1. Each block represents a man.

The process engineers are the key men of the organization since full responsibility for prosecution and coordination of all work on any particular project is in their hands. They refer chemical engineering design, instrumentation and preliminary capital estimation to the specialists indicated on the right. The process engineer must be a graduate in engineering but not necessarily chemical. He should preferably have had five years' experience in operations, in maintenance and plant engineering. He must know equipment and its uses and limitations. He must have a good knowledge of plant operation and understand the elements of plant operating costs. Such men are scarce in Canada, so scarce that it is now felt that incoming graduates must be selected shortly after their preliminary training course, earmarked for the chemical engineering section, and assigned for four or five years to jobs in the production division, which are carefully chosen to provide the necessary training.

The chemical engineer is a specialist. He is the man capable of calculating heat exchangers, absorption towers, distillation columns, etc. He knows chemical engineering thermodynamics. The company prefers a Ph.D. so wrapped up in his work that he is prepared to spend the rest of his life at it. Plant exper-

Fig. 1. Organization Chart.

## How It Works

Let us suppose that someone in the organization has had an idea for a new process and study has shown it to be theoretically sound. The next step in the development of the idea is a preliminary manufacturing study to determine profitability. The purpose of such a study is to try, honestly, to show that the proposal provides a reasonable chance for profit. The chemical engineering section is expected to provide preliminary capital and operating costs. As a rule there is little technical knowledge available at this stage and assumptions must be made. The engineer must overcome his habitual conservatism and make these assumptions on the most optimistic basis consistent with good sense. The preliminary manufacturing study must be an estimate of profitably assuming that everything goes well, or else good ideas may be rejected at this stage.

The project is assigned to a process engineer and it remains his responsibility from then on until it is either abandoned or in successful full-scale operation. In the preliminary study he somewhat arbitrarily selects unit operations for the proposed process and draws a descriptive flow sheet which shows each piece of equipment diagrammatically and provides space for tabulation of all basic equipment information. The process engineer proceeds to develop this information, sizing simple items like tanks and pumps himself, and turning things like heat exchangers and absorption towers over to the chemical engineer. At the same time the instrument engineer proceeds with his specialized function and the estimating engineer keeps an eye on design and suggests changes where he thinks capital costs can be reduced. He also proceeds with his estimate. When the flow sheet is done the process engineer tabulates power requirements and completes his operating cost estimate, and the estimating engineer completes his capital estimate.

The estimate is completed in three to five days, which is possible only because of rapid approximate design methods devised by our chemical engineer, the techniques developed by the estimating engineer, and the specialized knowledge of the instrument engineer. The accuracy of the estimates is at least as good as the over-all accuracy of the study at this stage. The flow sheet prepared in the preliminary study may be revised and refined out of all recognition as more precise information is obtained and more careful designs made, but it is never abandoned entirely and serves as a point of departure throughout the life of the project.

ience, though highly desirable, is not essential.

Although some modern processes simply could not be operated without modern instruments and although much instrumentation is required to ensure safe operation and for other similar basic reasons, the extent of instrumentation depends, like other plant design, mainly on the compromise between capital and operating costs which results in minimum over-all production cost. The large, rapid and continuing increase in the cost of employing a man has influenced this compromise in the direction of more instrumentation. In recognition of this, and because of the increasingly complex and specialized nature of industrial instrumentation, it is felt that the chemical engineering section can justify employing an instrument engineer.

This man does more than provide instruments at the request of the process engineer. He must understand the processes and operations used, and recommend economical instrumentation, and he often suggests process changes to achieve a better over-all design. The universities, probably rightly, do not graduate young men as instrument engineers so that a long period of postgraduate training is required.

It is believed that the necessity of locating an instrumentation enthusiast makes it undesirable to specify that he should necessarily be a chemical engineer. We selected a mechanical engineer, taught him basic chemical engineering, had him visit almost all our plants to study their equipment and operation and, incidentally, prepare a complete monograph of each, and finally sent him for training to all the major instrument companies.

In the opinion of this company any study of chemical manufacture should include a series of increasingly accurate forecasts of profitability. A rough approximation should be made at the idea stage, a second and more accurate after basic research, a third and still more accurate after bench scale plant operation, and so on. This procedure helps to minimize unprofitable development work. However, upwards of a dozen capital estimates may be required on only one project. Good design has twice already been defined as a compromise between capital and operating costs resulting in lowest over-all production costs. There are nearly always several ways of carrying out an operation and no two of them will have the same capital or operating costs. The only way to select the best is to make estimates, and it is not hard to imagine that the development of an optimum process may require literally dozens of such estimates. It is believed that efficiency has been greatly increased by making one man, the estimating engineer, responsible for capital estimates.

After certain basic qualifications are assumed, the interest of this man in his job is again of paramount importance. It was this company's good fortune to find a mechanical engineer with plant background and seven or eight years of plant design and equipment ordering in the company's engineering department. Following basic training in chemical engineering and industrial chemistry a program was laid out of collecting and collating cost information on whole plants—for example, contact sulfuric acid plants, on individual items of equipment, as for instance, pumps, and on piping and valves.

It is our company's opinion that successful operation of a chemical pilot plant requires a combination of chemical and chemical engineering theory and practical knowledge of equipment operation and maintenance seldom found in one man. Our present staff consists of two chemical engineers, one of whom has the fundamental knowledge and the other the practical experience. We have found that they make a good team.

If the results of the preliminary manufacturing study are encouraging—and usually they are not—the next step is in most cases the development of fairly basic chemical and physical information in the research department. This work may show that the chemical engineering section's plant design must be changed but the changes do not alter the preliminary nature of the flow sheet. Changes to capital and operating cost estimates may be required also and these in turn may lead to revision of the preliminary manufacturing study. In general, the chemical engineering section acts only as an observer at this stage.

The next stage of the development is probably the operation by the research department for the development division of a bench-scale plant to demonstrate the chemical feasibility of the whole process, step by step. The process engineer sits in on the design of this plant to assure himself that the unit operations used are feasible on a large scale and generally to ensure that his flow sheet and bench-scale design are basically similar. He also observes operation closely, making revisions to his flow sheet and operating cost estimates as definite information is developed. At the conclusion of the bench-scale work the chemistry of the process has been established and the capital and operating cost estimates are reasonably accurate from this point of view.

However, since unit operations were only arbitrarily selected and equipment only roughly designed, the flow sheet is still approximate from an engineering point of view. The most careful designs possible are required at this stage in order to reappraise the profitability of the project as accurately as possible before deciding to spend money on the next step, which is usually the erection of a pilot plant to prove the process and also because the pilot plant cannot be designed properly unless the full-scale unit operations have been established. The procedure used by the chemical engineering section in this careful design is the same as in the preliminary design except that rigorous methods are used and the capital estimate is checked by the engineering department.

If the second major appraisal of profitability shows that the project is still attractive, and it is decided to build a pilot plant, the process engineer in consultation with the specialists designs the process equipment, prepares a tabulation of service requirements and an operating cost estimate. These are then turned over to the engineering department personnel who make layouts, building, service and mechanical designs and prepare a capital estimate. The pilot plant supervisor sits in on all this work. An appropriation request is prepared by

the development division and on approval the engineering department proceeds with pilot plant construction. The process engineer is responsible for ensuring that the design is satisfactory from the development division viewpoint, and the pilot plant supervisor usually acts as field engineer during construction.

The chemical engineering section operates the pilot plant. We have found most useful an advisory committee consisting of the pilot plant supervisor, the chemical engineer, and representatives of the research department and pioneering section. We consider it important also to have the chemical engineer and the instrument engineer personally obtain the specialized knowledge which they require from the pilot plant.

Successful completion of pilot plant operation makes possible final revision of the full-scale process design. The development division makes a final study of profitability and if the project is still attractive submits a final report recommending the erection of a full-scale plant.

If the recommendation is accepted the chemical engineering section arranges to have the engineering department proceed with final full-scale plant layouts, building, service and mechanical design and a final capital estimate. The process engineer sits in on this work, provides all process information and generally ensures that the design is satisfactory to the chemicals department. When this is done the development division prepares an appropriation request and, on approval, construction is started by the engineering department.

The chemical engineering section represents the interests of the chemicals department during the construction period. It is responsible also for the preparation of complete operating manuals and for the initial operation of the plant. Its responsibility is at an end only when capacity operation within predicted costs has been established.

### Discussion

**H. Gordon Foucar** (Polymer Corp., Sarnia, Ont., Canada): In the organization that you indicated who has the responsibility of keeping the group busy with ideas? Who is the originator of the ideas?

**F. S. McCarthy:** The group within the division responsible for coming up with new ideas is the pioneering section.

**Einar West** (Hercules Powder Co., Wilmington, Del.): How many projects can you undertake at one time?

**F. S. McCarthy:** It obviously depends on the projects. At this particular moment we are keeping two major projects under way in the division and we also have, I should think, about a

dozen others in various stages of development, although most are in a fairly preliminary stage. Actually the chemical engineering section would not be working on more than two or three projects at any one time.

**William L. Williams, III** (C. F. Braun & Co., Chicago, Ill.): You spoke of the importance of the estimate. As I understand it, you make several estimates as you go along. And you use these to firm up the project.

Do you feel that information gained from industries dissimilar to yours can be applied to your case? Or do you need a separate summary from your own control department to insure a steady flow of good data on your own actual operations?

**F. S. McCarthy:** The answer is that we do both things. We do not feel that the information which is usually readily available is in a form ready for us to use. It requires that we do a considerable amount of collating and actually it has to be oriented in time.

**F. Gordon Foucar:** Could you tell us something about your method of choosing men for the pioneering section? Do you draw them from your own organization?

**F. S. McCarthy:** That is one of our major problems. We have been looking for men suitable for the pioneering section ever since it was started. We have never had a full complement of people. You ask how we go about finding men. The company receives applications from various sources and sometimes the personnel people send us likely looking young men and women. With luck we might get one person a year in this way. We also keep an eye on the young people in our own company who are getting the background and experience required for development work.

**G. W. Hatfield** (National Research Council, Chalk River, Ont., Canada): At what stage does the production group take over the plant from the chemical engineering group?

**F. S. McCarthy:** The chemical engineering section is responsible for the plant until capacity operation within predicted costs has been demonstrated. The production division takes over at that time. We use the initial operating period for completion of training of the operating personnel and supervisory force selected by the production division. None of these people has been as intimately concerned with the design of the plant as the responsible members of the chemical engineering section. The latter are presumed to be the experts and although this may sometimes be open to question it is still the presumption.

*(Presented at Montreal Meeting, Montreal (Que.), Canada.)*

# A Young Engineer Looks at His "Profession"

J. B. WEAVER

Olin Industries, Inc., East Alton, Illinois

OF what service to humanity is engineering? Is its contribution comparable to that of the older occupations more widely recognized as "professions"? If so, why are engineers not generally recognized as "professionals"? If the contribution is not comparable, why not, and can our contribution be increased? These questions have been of increasing importance to me as I pursue engineering.

For clarity and accuracy, the important terms should be defined—for example, an *engineer* as a graduate of an engineering course at an accredited college. Webster (29) defines *engineering* as "the art and science by which the properties of matter and the sources of power in nature are made useful to man in structures, machines, and manufactured products; the occupation and work of a professional engineer." Fifty-eight branches of engineering are mentioned. Definitions of *profession* range from "broadly, one's principal calling, vocation, or employment" to the much narrower one—"a calling in which one professes to have acquired some special knowledge used by way either of instruction, guiding or advising others or of serving them in some art." The dictionary recognizes three "learned professions"—theology, law and medicine. *Professional* is defined as "characteristic of or conforming to the technical or ethical standards of a profession or an occupation regarded as such."

Certainly engineering is a profession under the broadest definition above. When the question is recognition of the engineer by the public as a "professional," however, the second definition is what most engineers have in mind. Most engineers consider themselves as professional as doctors, lawyers, or ministers, and would like to have the public recognize this. It is generally assumed (34) that such recognition has not been granted; the dictionary's naming of only three learned professions bears this out, as does the recent minimum wage law (22).

## Characteristics of a Profession

Granting this public non-recognition as a fact, let us investigate whether engineering as a vocation generally fulfills the definition and characteristics of the vocations more widely recognized as professions. The minister, though considered a professional, will be omitted from much of the following discussion since his profession is so much less formalized. The characteristics mentioned in the dictionary definition of profession and professional are: (a) acquired special knowledge, (b) used in instructing, guiding, or advising others or of serving them, (c) technical standards, and (d) ethical standards. Dr. Warren K. Lewis (16) similarly phrases the characteristics as (a) sound training and technical competence in some field of specialization,

(b) "capacity for outstanding initiative and leadership in his field," and (c) "responsibility for intelligent and disinterested advice and service, not only to clients, but also to society as a whole." The new Wage-Hour Law (21) states the following: to qualify for professional exemptions "an employee must, as his primary duty, do work requiring knowledge of an advanced type in a field of science or learning customarily acquired by a long course of specialized intellectual instruction, or work that is original and creative in character in a recognized artistic field and the result of which depends primarily on the invention, imagination or talent of the employee. The work must be predominantly intellectual and varied in character and of such a nature that the output or result cannot be standardized in relation to a given period of time, and must require the consistent exercise of discretion and judgment."

Justice Brandeis (8) defined a profession as "an occupation requiring extensive preliminary intellectual training, pursued primarily for others and not merely oneself, and accepting as a measure of achievement one's contribution to society rather than individual financial advancement."

The following is a compilation of these definitions as the characteristics of the recognized professions:

1. Members with special training and knowledge
2. Standards to enhance fulfillment of (1)
3. Members who use training for service to public
4. Standards to enhance fulfillment of (3)
5. Enhancement of recognition of achievement of members in terms of public service.

The medical and legal professions certainly fulfill all these requirements. The education of doctors and lawyers requires more time than that required for an engineering degree. They are licensed by the states on the basis of training to meet the technical requirements of practice. Both professions gain most of their income from a direct consultative service to members of the public. In addition, the medical profession does a great deal of unpaid hospital work, and medical research has eliminated many diseases and developed countless valuable drugs and treatments. The legal profession has set up organizations to provide free legal help for the needy, and lawyers have been the main source of lawmakers and judges in our government ((35) 59% of 80th Congress). Members of these professions have thus served the public. Both professions also have ethical standards by which they agree to abide; doctors take the Hippocratic Oath (including (9) "the regimen I adopt shall be for the benefit of my patients according to my ability or judgment,") and lawyers take an oath before they are admitted to the bar ((12) for Massachusetts, including "I will not wittingly or willingly promote or sue any false, groundless or unlawful suit, nor give aid or consent to the same.")

As to measurement of achievement in terms of public service, income is far from the only criterion of advancement in these professions; the industry awards in the medical profession are rigidly tied to service to the public, and the underpayment of those widely recognized lawyers who go into public service is well known.

# WHITE SULPHUR SPRINGS

## MEETING PROGRAM

NOW that you know all about White Sulphur Springs (*See* "C.E.P.," January issue, p. 13)—its history, charm, and its facilities and pleasures that await you as an attendant at the A.I.Ch.E. meeting, March 11-14, in this issue we propose to give you an account of the technical program and what its progenitors plan to cover at the sessions.

The technical program, accompanying this account, is under the direction of Walter E. Lobo, of the M. W. Kellogg Co., who has arranged for booklets of complete preprints of the papers to be available to the members before the meeting. The idea back of this plan is to encourage and facilitate informed discussion at the symposium. Since the technical sessions will concentrate on one subject only, namely, "The Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment," it should be easier for members to contribute some worth-while ideas to this symposium and especially if previous study and thought have been given to the papers. The book of preprints may be obtained by remitting $2.50, to S. L. Tyler, Secretary of the Institute. Checks should be made payable to the A.I.Ch.E. The books will be mailed out in time for study prior to the meeting date. Purchase of books will also be possible at White Sulphur Springs.

◄ **Left to right: F. A. Otto, DuPont— vice-chairman, Local Committee on Arrangements, and A. B. Stiles, DuPont —member exofficio, Local Committee on Arrangements.**

▼ **Below—left to right: H. F. Lewis, DuPont—member, Registration Committee; G. W. Bradshaw, DuPont— member, Registration Committee; R. V. Green, DuPont—chairman, Registration Committee, and M. C. Guth. ie, DuPont —member, Registration Committee.**

### Sessions

Beginning with the first day, on Monday morning after a welcoming address by A. B. Stiles, technical superintendent, Du Pont Co., Belle Works, and chairman of the Charleston Section, A.I.Ch.E., J. H. Rushton, Illinois Institute of Technology, Chicago, will deliver his paper, "Applications of Fluid Mechanics and Similitude to Scale-Up Problems." This is a brief review of the principles of dynamic similitude and includes a general method whereby the requirements for dynamic similitude for any flowing system can be determined.

On that same morning before the luncheon recess the audience will hear a paper authored by Paul Talmey, Gregoire Gutzeit, and J. Robert Spraul of General American Transportation Corp., Chicago, titled "Relationship Between Test Data and Industrial Plant Equipment." Here three general classifications of engineering problems are discussed on designing full-scale commercial equipment. Filtering and settling are covered as examples in the first classification. Rotary dryer, pilot plant and field data are used as examples for the second group. In the third group, problems are discussed for which pilot plant tests are impossible or useless.

The afternoon session will include two papers—"Interpreting Small Scale Filtration Tests in Terms of Commercial Scale Equipment," by J. A. Kenney of the Oliver United Filters, Inc., New York, N. Y., and "Practical Evaluation of Pilot Plant Filtration Data" by R. N. Hill and M. M. Kaiser, both associated with the Eimco Corp., New York, N. Y. In the first-named, attention has been centered on the scaling-up procedure and the type of filtration determined beforehand but the paper has been organized to reveal some aspects of type selection. In the latter the authors make it plain that there is no substitute for performance tests when designing a plant to include vacuum filters or to get the most out of existing filters.

At the Tuesday morning session the paper, "The Relation of Pilot Plant Operation to Commercial Plant Operation in Selective Energy Absorption Freeze Drying," will be presented. It is

## A YOUNG ENGINEER

### Characteristics of Engineers

Does the occupation of engineering share
these characteristics? As to the training
and technical standards, I don't think any-
one questions the fact. These are assured
by the degree and in some cases state reg-
istration. The phrase "useful to man" in
the dictionary definition of engineering in-
dicates some degree of public service. An
engineer's main income does not stem from
a direct consulting relationship with the
public, however; service to the public is
definitely less *direct* than that from the
well-recognized professions. The question
of the importance of this service will be
considered in detail below.

An indication of the importance which
engineers attribute to public service can,
however, be induced from a survey (*30*)
which reported young engineers as being
less interested in "chance to be of public
service" in a job than in any of eight other
job incentives mentioned. Again, an indus-
try leader (*17*), and incidentally one who
has actively sought at other times to in-
crease the professional attitude among engi-
neers, recently compiled a list of ten "qual-
ities and attainments" needed in chemical
engineering which did not include any
mention of public service or interest in out-
side affairs—and another leader in the field
said he would be "hard put to add to" the
list of specifications. A psychological test-
ing survey of engineering students (*15*)
has also concluded that they are "de-
cidedly not so interested in the welfare type
of vocational activities as is the general
population." Engineering students scored
on the average lower than 61 per cent of
people in general in their interest in public
service.

In general, although the scientific method
he uses requires constant honesty of mind,
there are no formal ethical standards to
which an engineer must subscribe before
he can be considered a member of the
engineering profession, though some codes
have been suggested (*5, 13, 32*). In this re-
spect engineers are definitely unlike lawyers
or doctors. One writer (*18*) describes an
unwritten code to which he says engineers
adhere to rationalize a lack of consideration
of all the social implications of their work.
As to measurements of achievement in
terms of public service, engineers are sel-
dom considered an underpaid group, except
perhaps in early working years. The other
chief recognitions proffered by the profes-
sion are the awarding of medals and so-
ciety officerships. Although many recip-
ients have been of great public service, these
in general are awarded on the basis of
service to industry or the engineering pro-
fession, independent of whether or not
recipients have acted consistently as public
servants.

### The Engineer as a Public Servant

Developments by technologists (chem-
ists, engineers, and other scientists) (*16*)
have had a greater effect on the everyday
life of a United States citizen than have
the works of any other group. A recent
history of science has been written with
this as its major thesis (*27*). The relaxa-
tions of a movie, the routine of an elevator
ride, the safe efficiency of an airplane ride,
and the fear of an atom bomb—all day,
every day we live with and by scientific
developments. There is no question that in
bringing about such tremendous changes in

# Lever Brothers Company, too,
## gets **hydrogen** at low cost

ALMOST every hydrogen plant built during the past five years in the United States for fats and oils processors has been a Girdler HYGIRTOL* plant. A recent installation, shown above, is the Hammond, Indiana plant of Lever Brothers Company.

Why such widespread acceptance? . . . Because HYGIRTOL plants produce hydrogen of purities up to 99.8% *at the lowest cost* of all commercial methods! The plants use natural gas, propane and butane as process material and fuel. Operation is continuous, automatic, instrument-controlled and output can be varied readily from 50% to 110% of rated capacity. Only one operator per shift is required. Operation is clean . . . no dust or smoke or noise. It produces as much as 35 lbs. of pure carbon dioxide by-product for each 1000 cu. ft. of hydrogen.

Girdler designs and builds plants to produce, purify or use chemical process gases, liquid and gaseous hydrocarbons, and organic compounds. Write for information on how Girdler can serve *you!*

*HYGIRTOL is a trade mark of The Girdler Corporation



*Works speak louder than words*

### GAS PROCESSES DIVISION

THE *GIRDLER* CORPORATION

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## WHITE SULPHUR SPRINGS

authored by A. G. Blank and W. H. Zamzow of Proctor & Schwartz, Inc., Philadelphia, Pa. This paper reviews the principles of application of the selective energy absorption heat source related to freeze drying.

Just prior to luncheon on Tuesday C. M. Ambler's paper, "The Evaluation of Centrifuge Performance," will be presented. The conclusion is drawn in this work that in the field of centrifugal filters, the complete evaluation of commercial centrifuge performance is seldom possible and laboratory scale tests are only useful for comparative pur-



Mrs. I. L. Murray, chairman, Ladies Committee, and Roland Voorhees, Union Carbide & Carbon Corp., secretary, Local Committee on Arrangements.



Left to right: R. J. Valleau, American Viscose Corp.—member, Registration Committee; E. L. Bolick, American Viscose Corp.—member, Registration Committee; B. J. Haley, Union Carbide & Carbon Corp.—member, Hotel and Meeting Rooms Committee, and J. D. Lienhardt, W. Virginia Pulp and Paper—member, Transportation Committee.

poses. Mr. Ambler is associated with the Sharples Corp., Philadelphia, Pa. In the afternoon the Jones-Pyle paper will be heard. It is titled, "Scale-Up of Semi-Works Distillation Equipment." This paper suggests general methods for extrapolating semi-works data to plant-scale design, and possible sources of error are discussed. Both authors are in the employ of the Du Pont Co.

The technical sessions will conclude on Wednesday morning with two papers —"The Design of Commercial Continuous Reactor Systems from Pilot Plant Batch Data," by Arthur P. Weber of International Engineering, Inc., Dayton, Ohio, and "A Procedure for Scaling-Up a Catalytic Reactor,"—John Beek, Jr., and Emanuel Singer, both affiliated with the Shell Development Co., Emeryville, Calif.

Mr. Weber asserts that the solution to a typical design problem makes possible a comparison of batch vs. continuous operation to evaluate the desirability of going to continuous operation. Messrs. Beek, Jr., and Singer present in their paper a procedure for scaling up fixed-bed catalytic reactors. The example used is the production of toluene by the dehydrogenation of methylcyclohexane.

Not that White Sulphur Springs meeting will be all technical papers—as related in the January issue there will be cocktail parties, golf tournaments, plants trips and diversions for the ladies. Come one, come all. The dates— March 11-14 at the Greenbrier.

Left to right: M. M. Delancey, DuPont—member, Finance Committee; S. D. Smith, DuPont—chairman, Sports Committee; B. T. Woodruff, DuPont—chairman, Finance Committee.



Left to right: J. E. Crawley, DuPont—member, Sports Committee; M. W. Butenhoff, DuPont—member, Printing Committee, and W. A. Payne, DuPont—chairman, Printing Committee.

## A YOUNG ENGINEER

(Continued from page 20)

everyday life, the engineer has been a great influence on the public—and most of the developments have made life easier for that same public as consumers. However, the public exists in dual capacity; not only as consumers but also as workers, and the effects of the industrial revolution were not uniformly beneficial to workers. The major changes in the occupations and environment of workers brought hardships in many cases. Though scientific advance is commendable, interesting and necessary, the results may have bad as well as good effects on society.

Personal hardship, then, often has resulted from technological developments along with public service. Did the engineer, close to these developments and trained to a professional level, seriously consider these problems and try to plan for their alleviation? The total record of such consideration and planning has been small until recently (18), and the part undertaken by engineers has been even smaller.

This is a major difference from the professional manner of approach characteristic of doctors in the field of medicine and lawyers in the field of law. Enough members of each of these groups have on their own initiative investigated the deeper aspects of the problems with which their professions have been confronted to improve markedly the situation of the public in regard to those problems. Doctors have sought and found causes of diseases; lawyers have stepped into the field of lawmaking to improve the laws as they see public need. Engineers have seldom considered or sought a major role in solving the problems arising from their developments. As one nontechnical writer (31) puts it, "such narrowness impoverishes all of us." If engineers had taken the professional approach they would have better foreseen some of the social trouble wrought by technological change, and could have, in large numbers, undertaken a program to plan for their alleviation or solution. As Mott Souders, Jr., points out (25), the method of attack of the engineer is like that which any statesman must use, so that engineers should have been eminently qualified to undertake solution of problems raised by their developments.

Since engineering effort is chiefly along lines financially supported by industry, most projects are undertaken with a view toward making the highest possible profit for a company. While this does not by any means necessarily conflict with the public interest, such choice is not always along a line of maximum public need. That is, higher return on investment can be made in many fields other than those of public service. Engineering developments in the past decade have as often gone toward making life easier, more pleasant, more convenient—improvement in luxury items—as toward better public safety, housing, health, etc. Only recently have technologists in any great number turned the scientific method to solving problems of human relations.

### Conclusions

To summarize, it is my belief that our contribution can be increased if individual engineers will (a) use as a consideration in choosing a job the public service which it provides, (b) consider carefully the possible effects of their work on all people with a view toward foreseeing and minimizing personal hardships, and (c) keep sufficiently in touch with developments in all fields.

## FOR ENGINEERS WHO PLAN REGISTRATION

The Institute's Committee on Professional Legislation reports that at a recent meeting of the National Council of State Boards of Engineering Examiners, it was stated that as of June, 1950, there were 168,863 registered engineers in the United States. According to replies from 26 states, there were 18,647 engineers in training.

The Committee on Registration by Endorsement arrived at the following conclusions which should be interesting to engineers contemplating registration or already registered:

Conclusion 1. Written examinations should be waived for applicants who have successfully passed reasonably equivalent written examinations for registration in another state.

Conclusion 2. Written examinations should be waived in the case of applicants of long-established and recognized professional standing.

Conclusion 3. The requirement of oral examination or personal interview should be waived wherever possible in the case of out-of-state applicants of established qualifications who are registered in other states.

Conclusion 4. An engineer registered in other states should not be penalized for not securing registration in a given state before he actually needs such registration.

Conclusion 5. The registration and renewal fees for certification or registration by endorsement should be kept to a minimum.

Conclusion 6. The repeated checking of educational credentials, character references, and experience endorsements should be minimized.

John M. Weiss, chairman of the Institute's Committee, also reports that the Year Book of the National Council of State Boards of Engineering Examiners, obtainable from T. Keith Legare, executive secretary, Palmetto State Life Building, P.O. Drawer 1404, Columbia, S. C., price $2.00, has in it a list of membership of the various state boards, with the names and addresses of secretaries and members.

## ARMOUR REPORTS 337 PROJECTS IN 1949-50

Scientific progress on more than 150 varied research projects is described in an annual report issued recently by Armour Research Foundation of Illinois Institute of Technology. It covers the fiscal year 1949-50.

Armour's staff of almost 700 persons undertook a total of 337 projects, according to the 56-page report. This represented an investment of $4,614,958, an increase of 12.1 per cent over the previous year. Of the 337 projects active during the year, 182 were sponsored by industrial concerns, 94 by government agencies, and 61 by the Foundation itself.

The International division of the Foundation surveyed technological conditions for the Republic of El Salvador and Cuba during the year. A new industrial research institute was established in Mexico City by the Bank of Mexico, and an Armour staff member acts as director of laboratories there. Among the professional meetings sponsored by Armour last year were the first National Noise Abatement Symposium, the National Conference on Industrial Hydraulics, an international Symposium on Thin Films, and the Illinois Conference on Industrial Research.



Molding fused stabilized zirconia plates.

## NEW REFRACTORY ANNOUNCED BY NORTON

A new refractory product "which promises to open a new era in chemical oxide processing at ultra-high temperatures," was announced recently by the Norton Co., of Worcester, Mass., manufacturer of grinding wheels, grinding machines, and refractory products. This product, known as Fused Stabilized Zirconia will withstand in molded shapes temperatures up to 4600° F.

The trend in both research and production processes for the past several years has been toward higher temperatures which has created a demand for special refractories.

Fused zirconia was first made in Norton laboratories in 1946, which if now manufactured by the process then used, would sell for approximately $2.00 a pound. Further experimentation brought down the cost to the consumer to an average of 50 cents a pound in grain form.

According to D. W. Marshall, Norton research engineer, it will be possible

soon to make zirconia at Norton Co. that is purer than what is now sold as chemically pure zirconia. The basic steps are purification and fusion, controlling stability, composition of bodies regarding grain sizing, etc.

All these facts and more were brought out at a technical conference for editors held by the company Jan. 11, 1951, at Worcester at which time the Norton research program and the development of high temperature refractories were described by M. F. Beecher, director of research and development.

John Jeppson, works manager, abrasive division, explained the processes to be seen on the refractories and tunnel kiln plant tours. Later in the day L. H. Milligan, assistant director of research, talked on "Stabilized Zirconia as a Pure Oxide Refractory," S. S. Kistler, director of research, on the "Development of Stabilized Zirconia," and D. W. Marshall, research engineer, and O. J. Whittemore, ceramic engineer, talked on "Electric Furnace Fusion and Purification of Zirconia" and "Properties and Uses of Stabilized Zirconia Products" respectively.

## SAPIRIE, MANAGER, OAK RIDGE OPERATIONS

S. R. Sapirie, deputy manager of the Atomic Energy Commission's Oak Ridge operations, Oak Ridge, Tenn., was named manager there by M. W. Boyer, A.E.C. general manager. The appointment became effective February 1. Mr. Sapirie succeeds R. W. Cook who will succeed Walter J. Williams as director of production. Mr. Williams replaces deputy general manager Carleton Shugg, resigned.

Mr. Sapirie, deputy manager of the Oak Ridge Operations since October, 1949, has been associated with the atomic energy project for more than five years. He was assigned to the Manhattan Engineer District at Oak Ridge in 1946 as assistant director of operations, and later was chief of the operations division. With transfer of the atomic energy effort from the Manhattan District to the A.E.C., Mr. Sapirie was placed in charge of production and engineering for the Oak Ridge operations.

As manager, Mr. Sapirie will administer all programs for the A.E.C. at Oak Ridge. These include operation of the large uranium 235 production units and development work associated with them; the Oak Ridge National Laboratory with its extensive facilities for research and radioisotope production; the community of Oak Ridge and other related activities within the area.

## THIRD FURFURAL PLANT FOR QUAKER OATS

A contract for the construction of the Quaker Oats Co.'s chemical plant in Omaha was awarded to the Parsons Construction Co., Charles M. Holmes, plant manager, announced recently. The new plant is expected to be completed and in production by the end of 1951.

Major contracts for the chemical processing equipment to be used in making furfural have been let to the A. O. Smith Co., of Milwaukee, and the Vulcan Copper and Supply Co. of Cincinnati. The Milwaukee firm will supply the digesters for the manufacturing process and the Cincinnati company will supply the distillation equipment.

The Omaha plant will be the third chemical plant for the Quaker Oats Co. Other Quaker chemical plants are located in Memphis, Tenn., and Cedar Rapids, Iowa.

## PLANT MAINTENANCE BY HELICOPTER

Repainting a 150-ft. stack with a minimum interruption in plant operation was demonstrated recently with the aid of a helicopter at the Monsanto Chemical Co.'s plant in Everett, Mass.

The idea of using a helicopter was that of Russell L. Miller, plant manager. By calling on the aircraft, a day-and-a-half delay in painting operations was avoided—the time generally consumed in erecting scaffolding.

It was done this way: Steeplejack George F. Burgess of the Thomas J. Hind Co., Boston contractors, took off in the helicopter to the top of the stack. He took with him his staging hook, block and falls, and other equipment.

The pilot of the helicopter held it steady while the steeplejack leaned out the door and dropped his staging hook to the top of the stack. He then played out block and falls into the correct position. The helicopter descended and the steeplejack went to the base of the stack, slipped into the bos'n's chair attached to the rigging and went to work.

Total time, including take-off and landing: one-half hour.

## FELLOWSHIPS BY DU PONT FOR RESEARCH

The award of 78 postgraduate and postdoctoral fellowships to 47 universities, and grants-in-aid to 10 universities to "stock-pile" knowledge through the advancement of fundamental research, was announced recently by the Du Pont Co. An authorizationn of $390,400 was provided by the company for these awards. They are for the 1951-52 academic year.

It is expected that the program will help maintain the flow of technically trained men and women into teaching

and research work at universities and into technical positions in industry.

The grants-in-aid to universities are for unrestricted use in the field of fundamental chemical research. They provide $10,000 for each of 10 universities, all of which received similar awards for the present school year.

Institutions which will receive $10,000 grants each are: California Institute of Technology, Cornell University, Harvard University, University of Illinois, Massachusetts Institute of Technology, University of Minnesota, The Ohio State University, Princeton University, University of Wisconsin, and Yale University.

Of the 72 postgraduate fellowships to be awarded, all of which are predoctoral, 45 are in chemistry, 15 in chemical engineering, 5 in mechanical engineering, 3 in physics, 2 in metallurgy, 1 in biochemistry, and 1 in biology. The 6 postdoctoral fellowships are for work in chemistry.

Postgraduate fellowships in chemical engineering were awarded to Carnegie Institute of Technology, Columbia University, Cornell University, Massachusetts Institute of Technology, The Ohio State University, Princeton University, Yale University, University of Delaware, University of Illinois, University of Michigan, University of Minnesota, University of Pennsylvania, University of Tennessee, University of Texas, and University of Wisconsin.

## ELECTRO-CHROMIUM PLANT FOR CARBIDE

A new plant for the production of electrolytic chromium will be constructed at Sault Ste. Marie. Mich., by the electro metallurgical division, Union Carbide and Carbon Corp. It is expected to be in operation in the spring of 1951, and will adjoin Union Carbide's facilities there for the production of calcium carbide.

The electrolytic chromium operation will be based on a new process, important steps of which were developed by the Bureau of Mines, U. S. Department of the Interior. Other steps developed by the corporation's laboratories have been integrated with these to make large-scale operation economical. The metal will be of a higher degree of purity than commercially produced chromium metal now available.

## CHEMICAL PRODUCTS AT BRITISH FAIR

A full range of chemical products representing nearly all the leading British chemical houses will be featured at the 1951 British Industries Fair, according to the American Committee for the B.I.F.

To be staged in London and Birmingham, England, from April 30 to May 11, this annual trade show will embrace more than 1,000,000 sq.ft. of exhibits, with the chemicals section and allied products presented in London's Olympia Hall.

Among the products to be shown will be new types of anticorrosion compounds, chemicals derived from gasoline ranging from solvents to synthetic detergents and insecticides, soil fumigants, acids for use in glues, resins and disinfectants, chlorinated products suitable for use in antiseptic fluids, new fluorescent compounds, special preparations for the paint industry and many others. New equipment for the chemical industry also will be featured in this section, including laboratory apparatus, mass production equipment, new types of containers, and newly developed techniques in packaging for pharmaceuticals.

## NUCLEAR PHYSICS LAB. FOR YALE UNIVERSITY

A new $5,000,000 plant for nuclear physics work was recently announced by Yale University, New Haven, Conn. The university needs new facilities to carry on research in nuclear physics vital to national defense. The present physics laboratory was built in 1912. The new building will provide 110,000 sq.ft. of floor space for training physicists and teaching an annual average of 600 undergraduates and 80 graduate science students. A. Whitney Griswold, president of the university, said an effort would be made to raise the money by June of this year.

## SPAGHT ON BOARD OF SHELL CHEM.

M. E. Spaght was recently elected to the board of directors of the Shell Chemical Corp. Dr. Spaght is president of the Shell Development Co. He has been with Shell since 1933.

# MARGINAL NOTES

### Book on Basic
### Chemical Properties Revised

**The Chemistry of the Nonbenzenoid Hydrocarbons. Benjamin T. Brooks. Reinhold Publishing Corp., 330 W. 42nd St., New York, N. Y. (1950) 615 pp. $12.00.**

*Reviewed by C. L. Brown, Assistant Manager, Research and Development Department, Standard Oil Development Co., Esso Research Center, Linden, N. J.*

THIS book deals with the chemistry of the hydrocarbons of the paraffinic, naphthenic, olefinic, polyolefinic, terpene, and acetylenic series; that is, as indicated by title, with the chemistry of the hydrocarbons other than the aromatics. This edition constitutes a thorough revision of the first edition which appeared in 1922 and was for years a standard reference book in petroleum laboratories.

The present volume is a comprehensive reference book, with numerous references to the periodical literature. Complete coverage of all the patent literature has not been attempted, as was the case in the volumes by Ellis entitled "The Chemistry of Petroleum Derivatives." This omission of patent references has allowed, however, more discussion of the basic chemistry involved in hydrocarbon reactions. In a number of instances hydrocarbon reactions are discussed with clarity from the viewpoint of current reaction mechanism theories. Electronic interpretations of the more common reactions, including the carbonium ion approach, are given where applicable. The sections on oxidation are good from an organic chemical viewpoint but no attempt has been made to go deeply into combustion phenomena. The first chapter dealing largely with the nature and properties of crude petroleum is an interesting introduction to this subject. Part of this chapter deals with theories relating to petroleum formation.

The text is up to date from the viewpoint that practically all known reactions of the nonbenzenoid hydrocarbons are given at least some mention. The value of the book as a reference would have been enhanced had more references to reviews covering captured German literature been included.

Commercial developments such as catalytic cracking, alkylation with sulfuric and hydrofluoric acids, hydroforming, GR-S and butyl rubber manufacture, and ethyl and isopropyl alcohol preparation, are described and are discussed from the chemical viewpoint. Almost no information on these processes is presented from the chemical engineering standpoint. This was not to be expected, judging from the title and the preface to the book. However, reference lists afford ready opportunity to obtain sources of process data on the commercial developments mentioned in the book.

The subject matter is presented for the most part in a form which should allow easy reading by most chemical engineers and chemists. Chemical formulas and equations are given in sufficient number to provide a working knowledge to readers possessing a limited acquaintance with organic chemistry. The printing is legible and the binding and other mechanical construction features are probably adequate for most uses.

Among chemical engineers, this book would appear to be of most interest to those who are strongly interested in the chemical reactions of the nonbenzenoids and who wish to have a reference book supplying the basic chemical properties and the current theoretical explanations associated with the chemical reactions.

### "Oil, The Great Mover"

**Oil for the World. Stewart Schackne and N. D'Arcy Drake. Harper & Brothers, New York (1950) 128 pp. $2.50.**

*Reviewed by H. R. Glennon, Manuscript Editor, Chemical Engineering Progress.*

AS with still water so with unseen oil —it runs deep. This fact and many others are brought to light in this story of crude oil by two able storytellers—one a petroleum engineer and the other experienced in public relations. What could make a happier combination for bringing home to the layman and the technical man, too, the performance account of this natural resource and its many derivatives, and the research which is continuously going into the improvement of gasoline, fuel oil, and lubricants.

A feature of the book which aids easy reading is its make-up—fine letterpress, action and candid photographs, maps and charts. Then, too, the easy and informal manner of Messrs. Schackne and Drake permit the readers' retrospect to some ten million years ago when crude oil was formed up to the present time when many thousands of people invest their money in oil and depend on it for their income. It is the authors' belief that for hundreds of years to come there will be enough oil in the world, a conviction held by those (including this reviewer) who at one time or another prepared statistics on crude production in the United States, Soviet Union, Venezuela, Sumatra, Bahrein, etc.

Nor have the authors overlooked the needs of the technical reader in preparing this work. Here are assembled data on drilling, refining, transportation, etc. The oil *business* is less than a century old—a short period indeed when viewed in the light of its accomplishments and benefits for mankind. Here in an abbreviated version the reader is reminded of the benefits of "Oil, the great mover," as these authors call it, and especially of American contribution in skill and enterprise in promoting the petroleum industry.

### Books Received

**A Glossary of Terms in Nuclear Science and Technology. Section V—chemical engineering. Section VI—biophysics and radiobiology. National Research Council Conference on Nuclear Glossary. American Society of Mechanical Engineers, New York. (1950) 60 cents each.**

**Advanced Organic Chemistry. Reynold C. Fuson. John Wiley & Sons, Inc., New York, N. Y. (1950) 670 pp. $8.00.**

**Analytical Absorption Spectroscopy— Absorptimetry and Colorimetry. M. G. Mellon, editor. John Wiley & Sons, Inc., New York. (1950) 618 pp. $9.00.**

**Technical Publications 1948. Arman E. Becker, editor. Standard Oil Co. (New Jersey) and affiliated companies. (1950) 512 pp.**

**The Biochemistry of the Nucleic Acids. J. N. Davidson. John Wiley & Sons, Inc., New York, N. Y. (1950) 164 pp. $1.75.**

**The Identification of Molecular Spectra. Second edition revised. R. W. B. Pearse and A. G. Gaydon. John Wiley & Sons, New York. (1950) 276 pp. $8.50.**

# Here's the dope on 2

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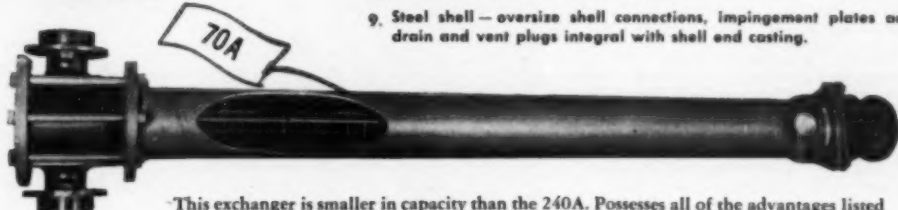
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# SECRETARY'S PAGE

## S. L. TYLER

**The report of Council and Executive Committee meetings held in December, 1950, and January, 1951, appear on page 41.**

## ANNUAL REPORT OF COUNCIL

THIS is a report of the activities and actions of the Council of the Institute for the period Nov. 1, 1949 to Nov. 1, 1950. There were nine (9) meetings of Council held during this period and the Executive Committee held twelve (12) meetings. The Council meetings were held on the following dates: Nov. 11, 1949, Dec. 4, 1949, and in 1950—Jan. 6, Feb. 10, April 7, May 28, July 7, Aug. 11, and Oct. 6. The Executive Committee meetings were held on the following dates: Nov. 10, 1949, Dec. 13, 1949, and in 1950—Jan. 6, Feb. 10, March 9, April 6, May 12, June, July 7, Aug. 11, Sept. 21 and Oct. 6. All these meetings were reported on the Secretary's Page in *Chemical Engineering Progress*. Therefore, this report is a summation of the actions taken during the entire year.

### Membership

The membership of the Institute has continued to grow although with not quite the same net increase as previous years. The number of new members elected was 1,043 compared with 1,154 for a similar period a year ago. Because of an increase in resignations, 138 this year, 87 last year, and approximately the same number dropped for nonpayment of dues, 217 against 205, the net increase is lower by 164, making the net figure 657 for this year compared with 821 a year ago. The following tables give the membership as of Nov. 1, 1949 compared with Nov. 1, 1950:

| Membership | Active | Associate | Junior | Total |
|---|---|---|---|---|
| Nov. 1, 1949 | 3,670 | 447 | 5,594 | 9,711 |
| Elections | 354 | 45 | 644 | 1,043 |
| Deceased | 15 | 1 | 5 | 21 |
| Resigned | 21 | 11 | 106 | 138 |
| Dropped | 21 | 4 | 192 | 217 |
| Elections rescinded | 1 | 1 | 8 | 10 |
| Nov. 1, 1950 | 3,966 | 475 | 5,927 | 10,368 |

| Membership | 1949 No. | % | 1950 No. | % | % of Increase 1950-49 |
|---|---|---|---|---|---|
| Active | 3,670 | 37.8 | 3,966 | 38.2 | 8.1 |
| Associate | 447 | 4.6 | 475 | 4.6 | 6.3 |
| Junior | 5,594 | 57.6 | 5,927 | 57.2 | 5.6 |
| Total | 9,711 | 100.0 | 10,386 | 100.0 | 6.8 |

### Publications

*Chemical Engineering Progress* has continued to be the one official publication of the Institute. The circulation has increased both to Institute members and through subscriptions.

During the year 425 copies of Vol. 25 of the Transactions of The Institution of Chemical Engineers (London) for the year 1947 were distributed, all on order basis. A second publication of The Institution of Chemical Engineers, "Particle Size Analysis," was also distributed to members of the Institute on the same basis—190 copies were ordered.

There has been considerable discussion in Council on methods of making further publications available to the membership. No definite decisions have been made on this except that Council has authorized the publication of certain symposia as separate volumes apart from *Chemical Engineering Progress* to be made available at cost to those members who are specifically interested. This would be a far more economical method of publication than to publish material of somewhat limited interest in *Chemical Engineering Progress* and distribute it to members.

### Meetings.

During the year the Institute has continued to follow the four-meeting pattern, that is, three regional and one annual. The annual meeting in 1949 was held at Pittsburgh, Dec. 4-6 and the attendance there 1,803. A regional meeting was held in Houston, Tex., Feb. 26-March 1, with an attendance of 813. Regional meetings were also held at Swampscott, Mass., May 28-31, with an attendance of 616, and at Minneapolis, Minn., Sept. 10-13 and the attendance there was 520.

### Amendments to the Constitution

At the annual meeting in Pittsburgh amendments to the Constitution were proposed by the Council and discussed at length. These amendments dealt mainly with the requirements for membership and the establishment of a Student grade of member. The final action at Pittsburgh was approval of the amendments with some slight modifications from their original form and as a result of vote by the Active members, these became a part of the Constitution.

### Accrediting

The Institute has continued to be extremely active in the accrediting of chemical engineering curricula. The Chemical Engineering Education and Accrediting Committee has been working closely with the Committee on Engineering Schools of the Engineers' Council for Professional Development and as a result of their joint efforts Council has approved their recommendations in newly accrediting or reaccrediting undergraduate chemical engineering curricula at 29 schools.

### Awards

At the Awards Dinner held during the annual meeting in Pittsburgh the Professional Progress Award in Chemical Engineering was presented to Mott Souders and as is the practice he acted as the speaker at this dinner. The William H. Walker Award was presented to Dr. W. H. McAdams in recognition of his outstanding contributions to chemical engineering literature mainly in the field of Heat Transfer. The Junior Award was presented to E. G. Scheibel in recognition of publications in the field of Extraction and Extractive Distillation. The Student Contest Problem Awards were also presented during this dinner and the recipients were: The A. McLaren White Award or first prize, W. E. Henderson of the University of Illinois. This prize carried with it a check for $100. The winner of the second prize was Irving Begelman of Cooper Union who received a check in the amount of $50. The third prize went to J. Wallace Crawford of the University of Illinois and with this was a check for $25. Honorable mention and a check for $10. were presented to F. A. Frick and C. E. Eberle of Washington University and R. P. Stein of Pratt Institute.

During the year Council has approved further recognition by awards and prizes of activities within student chapters and among students. The Student Scholarship Award which up to this year consisted only of the awarding of a certificate of recognition for high standing in the freshman and sophomore years of the chemical engineering curriculum was increased to include Student membership and a Student Member Pin as well as a two-year subscription to *Chemical Engineering Progress*.

In order to encourage the holding of student chapter conferences the Council has approved a small sum of money to be made available as first and second prizes in recognition of excellence of presentation of papers at these meetings.

### Local Sections

There have been seven (7) new local sections authorized during the year. The officers of the Institute in as far as it has been possible have appeared as speakers at local section meetings and it is hoped that this activity may be expanded considerably, but it should be noted here that the officers have been able to make many more such contacts during this year than in previous years. The new sections which were formed were: Twin City (Minneapolis-St. Paul), New Jersey, Texas Panhandle (Borger), Columbia Valley (Richland, Wash.), Washington, D. C., Central Virginia, Sabine Area (Tex.).

### Student Chapters

The Council has spent a considerable amount of time discussing the general question of student chapters and this is evidenced by the increased recognition of student scholarship as reported here. Five new student chapters have been authorized during the year at: Lehigh University, University of Maine, Newark College of

## EQUIPMENT

**2 • SPECTROMETER.** The Perkin-Elmer Corp. offers a new mobile Model 12-C infrared spectrometer. Designed for mobility, and faster recording, for on-the-spot analyses. The mobility is afforded by caster-mounting the cabinet and the whole unit will easily pass through ordinary doors and can be taken into the pilot plant for evaluation. Storage space provided for necessary accessories.

**5 • CORROSION-RESISTANT TUBING.** The Carpenter Steel Co. has a new line of tubular products in Carpenter Alloys B and C. Alloy B is effective in resisting hydrochloric acid in all concentrations and temperatures. It is also recommended for sulfuric acid at temperatures above 80° C. However, it is not suitable for oxidizing atmospheres. Alloy C will withstand strong oxidizing conditions, since it is part chromium and can be used with nitric, free chlorine, acid solutions of ferric and cupric salts. Also used for phosphoric, acetic, formic, and sulfuric acids. Tubing available, annealed and pickled, from ⅝-in. through 4½-in. diameter.

**7 • TURBO DRYER.** For handling heat-sensitive materials which have a tendency to foul, the Wyssmont Co. has designed and built several new Turbo dryers with external heating unit. Primarily for use on plastics, waxes, etc. Path of material to be dried follows the usual Turbo design, being fed through an opening in the roof and spread on the top revolving shelf. Before the material revolves back to the point of the feed opening, it is wiped or plowed off the tray, to the one below. The new dryer does not reheat the air but uses it only once in going through the dryer. Internal fans circulate the air within the unit.

**10 • SERRATING TOOL FOR KARBATE.** For serrating Karbate graphite pipe, National Carbon division offers a new hand serrating tool. Since flexible couplings are used in fitting impervious graphite pipe where flexible joints are required, the effectiveness of the joint depends to a considerable extent upon the quality of the serrations on the pipe. The new tool is simple, rugged and easy to use on the job. Pipe sizes from 1 in. to 6 in. may be serrated.

**12 • REMOTE SPEED CONTROL.** A mechanical remote control for variable-speed-electric power drives, developed by Sterling Electric Motors, Inc. The control is available in a variety of types such as the extended flexible cable or an extended rod with universal joint, etc. This new type of control permits variable-speed drives to be controlled from a distance where such a distance would be beneficial or necessary.

**14 • SOAP CRUTCHER.** Patterson Foundry & Machine Co. has a new heavy duty soap crutcher for the processing of soaps of all varieties, from toilet to hand soaps. It is also designed for use in the manufacture of metallic soaps, rust-prevention compounds, and many other specialties. Jacketed, it will withstand 125 lb./sq. in. pressure. Any desired capacity may be fabricated.

**15 • HIGH-PRESSURE DISPLACEMENT METER.** The Rockwell Manufacturing Co. for metering wide ranges of gas at a take-off point up to 1000 lb./sq. in., has a new high capacity positive displacement meter. Diaphragm-type meters according to the manufacturer have heretofore been limited to 500 lb./sq. in. The new meter is made of high tensile alloy steel and has a capacity of 31,000 to 46,000 cu.ft./hr. of gas. Many new design features are incorporated: relief valve system to protect diaphragm and mechanisms, gear-type valve movement, Teflon stuffing boxes, etc.

**18 • KELLY PRESSURE FILTERS.** Oliver United Filters, Inc., has a new line of Kelly pressure filters designed for clarifying molten sulfur. Five different sizes are available in packaged units with all auxiliaries and accessories ready-to-operate. A new improvement is a simplified internal manifold-type leaf outlet with single external connection. Units are jacketed to maintain proper temperature and while designed primarily for handling molten sulfur, other uses in the process industries are contemplated.

**19 • MINIPUMP.** For metering liquids in quantities as small as a few cu.cm./hr. the Milton Roy Co. has developed a new miniPump. Applications include laboratory and research work, pilot plant and semi-plant scale operations. Essentially its use is for metering small volumes of liquids into larger volumes of material such as injecting odorants into

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Cards valid for only six months after date of issue

# Chemical Engineering Progress Data Service

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natural or bottled gas, antifreeze into air or gas lines, adding vitamins to products, dyes to paper stock, etc., for formulating and blending work. Liquid end is Carpenter 20 stainless steel. Valve caps and clean-out plugs are sealed against pressure by O rings. Packing normally is Teflon. Plunger stroke is readily adjusted while operating to vary delivered volume from zero to full rated capacity.

**21 • FILTERING MEMBRANE.** For its line of industrial filters Titeflex, Inc., designed a new type of filtering membrane of 316 stainless steel wire formed to a screen of cylindrical shape. Used within the filter itself, these cylinders speed up filtration processes. Because of the shape, clogging is eliminated and cleaning effected without manual labor. The new screen membranes have a high efficiency because the back-wash flow reaches its highest velocity at the exact point of support of the filter cake. May be utilized with various types of filtration equipment. Available in any alloy that can be drawn into wire.

**22 • AEROPASS CONDENSER.** For plants that use 400 tons of refrigeration or over the Niagara Blower Co. developed a new aeropass condenser which makes use of a Duo-Pass precooling coil and an Oilout oil separator. The new condenser

removes all entrained oil vapors as well as cooling and condensing the refrigeration gas. By evaporation approximately 1000 B.t.u. are removed from each pound of water evaporated, and by removing superheat previously there is no tendency for salt to precipitate and clog the condenser coil banks. Full information. as well as flow diagrams are available.

## CHEMICALS

**30 • BETA GLUCURONIDASE.** Sigma Chemical Co. is producing in commercial quantities, bacterial beta-glucuronidase, an enzyme for use in biochemical research programs. The material is available as a prepared solution or as a dry powder.

**31 • 4-VINYLPYRIDINE.** For the chemical industry, 4-vinylpyridine is available from the Reilly Tar & Chemical Corp. This material is slated for use in the manufacture of synthetic elastomers, plastics, textile chemicals, photographic chemicals, etc.

**32 • HEXACHLOROCYCLOHEXANE.** Pennsylvania Salt Mfg. Co. has available large commercial quantities of hexachlorocyclohexane. Essentially a free-flowing white material, it is composed of the insecticidally inactive alpha and beta isomers of benzene hexachloride.

**33 • FORMCEL.** Solutions of formaldehyde in various alcohols are available from the Celanese Corporation of America. Material is made at the Bishop (Tex.) plant of the company and is currently being sold in 55% solutions of formaldehyde in methanol and 40% solutions in butanol, propanol and methanol. The water-free solution of formaldehyde can be handled at regular temperatures in standard equipment. For use by companies whose processes are based on a formaldehyde-alcohol end product.

**34 • ADSORPTIVE POWDER.** Attapulgus Clay Co. has a new product, Attaclay SF an ultrafine, dry, lightweight, free-flowing powder for use as a filler, flattener, conditioner, coater, polisher, etc., for the chemical, coating, paint, plastics, insecticide, etc., industries. Chemically a hydrated aluminum magnesium silicate, it is inert and neutral. Particles are in the subsieve size, 90 to 95% by weight being finer than $10\mu$. Bulk density is 13-15 lb./cu. ft.

**35 • GLACIAL ACETIC ACID.** Niacet chemicals division of Union Carbide & Carbon Corp. has a bulletin on glacial acetic acid giving the physical and chemical properties, latest specifications on the standard CP and USP grades as well as the shipping and handling information. Bulletin gives the applications of acetic acid as well as the operating procedures for diluting, testing for purity, methods of unloading tank cars and drums. Tables give freezing points of acetic acid solutions, specific gravity, dilutions, etc.

**36 • SCINTILLATION PHOSPHORS.** For use in scintillation detector units, Tracerlab, Inc., has now available two phosphorous materials. One is a synthetically grown hydrocarbon crystal known as Stilbene and the other is a solid plastic phosphor. The plastic phosphor is essentially a solution of terphenyl in a styrene monomer, the whole mass being polymerized into a solid. The phosphorescent materials are for high efficiency use in gamma count-

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ing, cosmic ray research, and fast neutron counting.

**40 • OXYGEN ANALYZER AND RE-CORDER.** Arnold O. Beckman, Inc., has a six-page bulletin explaining a new oxygene analyzer and recorder. The principle of operation of the instrument is explained, method of measurements and various types of analyzers are shown. Complete details are given as to the construction of the machines, uses, physical dimensions, responses, etc. For use in the chemical, petroleum, agricultural, metallurgical, etc., industries for oxygen control and manufacture, processing gases, chemicals, etc.

**41 • ION-EXCHANGE SYSTEMS.** Penfield Manufacturing Co., Inc., is offering a packet of information on its ion-exchange systems. Contains double sheet descriptions of seven different models of ion-exchange units of various capacities. The sheets show the ion-exchange unit, schematic diagram, and description of the parts, specifications, performance of each system which ranks in capacity from 5 gal./hr. to 1000 gal./hr. Performance chart also gives a table showing the chemical cost per thousand gallons of processed water for any raw water condition.

## BULLETINS

**42 • RECORDING AND CONTROLLING GRAVITOMETER.** For recording the specific gravity of a continuously flowing sample of liquid under actual line conditions, the American Recording Chart Co. has issued a bulletin on its new recording liquid gravitometer. The recording gravitometer is used on pipe lines, refineries, gasoline and chemical plants, etc., the record being made on a chart, and all records are at 60° F. owing to the fact that a special thermostatic coil is used to bring the liquids to the proper temperature. Can be used under high pressure. The recording-controlling liquid gravitometer is used for controlling or blending of two or more liquid products. It determines specific

gravity in the same manner as the standard gravitometer, in addition a controlling mechanism is provided which can be preset to operate the pipeline, refinery still, etc., to any specific gravity. Bulletin shows typical installations, line drawings, etc.

**43 • LEFAX CATALOG.** A new 1951 technical data catalog of Lefax is off the press. It contains a complete index of all the Lefax pocket size technical books offered by the company. Includes data on engineering, business, chemistry, surveying, metallurgy, chemistry, etc. Contains more than 2000 listings.

**44 • SWIVEL FITTINGS.** A catalog of ball-bearing swivel fittings from the Rasmussen Manufacturing Co. Made in either high pressure or low pressure types. The high-pressure type can be designed to handle pressures up to 15,000 lb./sq. in. and temperatures of 225° F. Single, double or triple swings and a full 360° rotation. Various packings can be used. The catalog gives all data on the different fittings made, giving the maximum pressures, corrosive substances, temperatures, operating data, sizes, dimensions and prices. Made in eight different styles of fittings, catalog gives complete data.

**45 • WELDED FLOATS.** Welded floats of stainless, Monel, steel, chrome, etc. Spherical, eliptical and cylindrical shapes from 2 in. to 4 in. in diameter, are described in the catalog of W. H. Nicholson & Co. The floats can be used not only in traps but also in the chemical, dairy, food-process industries for buoyancy or weight mediums, for operating mechanism chambers or vessels for storing gases and fluids for instruments of different types, etc. The catalog gives the construction of the welded floats and gives the types of connections. Tables give list prices, buoyancies, collapsing pressures, dimensions, etc.

**47 • METHACRYLATE-PLATING EQUIPMENT.** For the electrochemical industry, and for plating firms, the Singleton Co. has created pickling baskets of metal methacrylate resin which they claim last up to 100 times longer. The company also makes a Lucite tank for electroplating and chemical processing.

**48 • CAPACILOG.** Wheelco Instruments Co. has a new bulletin describing its capacilog line of electronically operated chart recorders. Used in process industries for the measurement, indication control, and permanent record of such variables as temperature, speed, static strain loads, a.c.-d.c. voltage and amperage. Bulletin explains operation and construction of the capacilog, gives specifications and explains how

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direct deflection, Wheatstone bridge circuit, and pneumatic-control types of operating systems are applied to the capacilog.

**50 • PROCESS EQUIPMENT.** From the Sturtevant Mill Co., a catalog describing its line of crushers, mills, laboratory machines, dry batch mixers, batch blenders, air separators, and vibrating screens. Manufacturers of heavy equipment, the bulletin in each case describes the kind of equipment made and shows a picture of it as well as the sizes.

**51 • ACRYLIC MOLDING INFORMATION.** Rohm & Haas Co. has issued a small booklet giving practical information on molding techniques and molding troubles and methods of overcoming these troubles, for acrylic resins. Booklet gives typical molding formulations and conditions and describes the various defects that are to be encountered in molding, giving suggested remedies as to how to overcome them.

**52 • CHEMICAL FEED SYSTEMS.** A reprint by %Proportioneers, Inc.% of a talk given by R. P. Lowe on "Chemical Feed Systems." It is 12 pages, covers various types of chemical feeding such as disc feeding, oscillating, gravimetric, rotary, fluid piston, pot, decanter solution feeding, etc. Exhaustive description of various methods of feeding chemicals to chemical systems.

**53 • FLUID FLOW TESTING.** Fischer & Porter Co. offers a technical report on fluid flow rate-testing. Though primarily designed for aircraft engines and accessories, it is a primer on flow characteristics through the rotameter, and should be of value to engineers in the petroleum and fuel industries. Covers all the theories of measurement with such instruments and shows how the flowrator has been applied to the measurement of jet fuels, etc. Describes the newest calibration techniques and illustrates modern precision accuracy calibration panels.

**54 • THERMOCOUPLE AND PYROMETER CATALOG.** The Bristol Co. has just published a new edition of its thermocouple and pyrometer accessories bulletin. The catalog lists many new items and contains new data on the proper application and use of thermocouples. The 56-page catalog contains illustrations of the various kinds of thermocouples and accessories and replacements, describes the various thermocouple types, the factors affecting thermocouple life, etc. Charts show how to select the right thermocouple and protection tube, and a user's manual gives the industry, temperature, application and the usual recommended materials for thermocouples. A large section of thermocouple calibration data round out the catalog.

**56 • CENTRIFUGAL OPERATING PRINCIPLES.** Operating principles and applications for two types of high-speed horizontal centrifuges which continuously remove solids from slurries and suspensions, are explained in a new bulletin by The Sharples Corp. Bulletin permits direct comparisons of design and function of a centrifuge equipped with a conical rotating bowl for handling a firm body or crystalline-type solid and one with a cylindrical bowl for handling relatively soft or plastic solids. Completely illustrated with data on operation, and specifications.

**57 • LABORATORY SAFETY.** The Fisher Scientific Co. has a newly revised edition of a 40-page Manual of Laboratory Safety. First section covers a method preventing accidents in the laboratory; second section is on laboratory first aid and fire fighting; another on safety equipment available for use in laboratories.

**58 • DRYERS.** A description of more than 30 types of Standard-Hersey dryers is given in a new company bulletin. Construction details of the dryers are shown, examples of where and how the various types of dryers are used, as well as illustrations of typical installations. Also describes a pilot plant dryer which can be adjusted to duplicate within reasonable exactness, the performance of any type rotary dryer on a laboratory test basis.

**59 • MICROFILMING.** The Micro-Photo Service Bureau is offering a 12-page illustrated booklet on "Facts and Figures on Microfilming Engineering Drawings. It presents pertinent information on preserving important engineering drawings and records, and gives the complete story in question and answer form, of what microfilming can mean in saving space and of records. Equipment is illustrated as well as the plan of the company.

**60 • DETERMINING SOLIDS IN BOILER WATER.** Hall Laboratories, Inc., in a new bulletin describe a quick and simple method for determining the solid content of boiler water or condensate. Almost instantaneous determination of solids is possible.

**61 • FLY-ASH HANDLING SYSTEMS.** A new booklet offered by Beaumont Birch Co. gives detailed information on their hydraulic and pneumatic ash and fly-ash handling systems. Uses a question-and-answer technique. Complete drawings and illustrations round out the booklet so that any engineer with such a problem would benefit from the information given.

**62 • AIR AND GAS COMPRESSORS.** Pennsylvania Pump & Compressor Co. has a four-page bulletin describing the various air and gas compressors made by the organization. Horizontal single-stage, doubling-acting straight-line type, driven by V-belts, flat belts, or directly connected to motor or steam. Table gives sizes and capacities of standard units. Units are pictured and one large center sectional view shows a cutaway of the single-stage compressor.

# CANDIDATES FOR MEMBERSHIP IN A. I. Ch. E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E. which states:

Election to membership shall be by vote of the Council upon recommendation of the Committee on Admissions. The names of all applicants who have been approved as candidates by the Committee on Admissions, other than those of applicants for Student membership, shall be listed in an official publication of the Institute. If no objection is received in writing by the Secretary within thirty days after the mailing date of the publication, they may be declared elected by vote of Council. If an objection to the election of any candidate is received by the Secretary within the period specified, said objection shall be referred to the Committee on Admissions, which shall investigate the cause for such objection, holding all communications in confidence, and make recommendations to the Council regarding the candidate.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before *March 15, 1951,* at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st St., New York 17, N. Y.

## APPLICANTS FOR ACTIVE MEMBERSHIP

Roger J. Altpeter, *Madison, Wis.*
Proctor H. Avon, *Wellesley Hills, Mass.*
Philip H. Bailey, *Glen Burnie, Md.*
William L. Bolles, *Texas City, Tex.*
Robert A. Clarke, *Chicago Heights, Ill.*
E. T. Darden, *New Castle, Del.*
Corwine S. Davis, *Succasunna, N. J.*
L. S. DeAtley, *Kansas City, Mo.*
Raymond Duddleston, *Midland, Mich.*
J. E. Ekhaml, *Waynesboro, Va.*
James C. Feldmann, *Penns Grove, N. J.*
Louis E. Garono, *Woburn, Mass.*
King I. Glass, *El Dorado, Ark.*
Frank A. Gluckert, *West Chester, Pa.*
Edward E. Gray, *Wilmington, Del.*
John T. Hale, *Wilmington, Del.*
Bernard A. Hess, *Wilmington, Del.*
John S. Hole, *Drummondville (Que.), Canada*
Karol L. Hujsak, *Tulsa, Okla.*
Charles F. Kelly, *Deepwater Point, N. J.*
R. O. Kettner, *Woodstown, N. J.*
Wilfred H. Molinari, *Penns Grove, N. J.*
Earl D. Morris, *Midland, Mich.*
G. B. Otto, *Wilmington, Del.*
Walter M. Otto, *Akron, Ohio*
Norbert Platzer, *Springfield, Mass.*
Harold H. Radke, *Lorain, Ohio*
G. E. Riker, *Penns Grove, N. J.*
Harold Ten Broeck, *St. Albans, N. Y.*
T. Eugene Tonnessen, *Claymont, Del.*
James Elton Tuohig, *Elizabeth, N. J.*
A. B. Welty, Jr., *Linden, N. J.*
Robert C. Werner, *Harmony, Pa.*
Henry E. Wessel, *St. Louis, Mo.*
C. W. Wilkins, *Jacksonville, Fla.*
John T. Wilson, *Freeport, Tex.*
C. F. Winans, *Foxboro, Pa.*
Robert J. Wolf, *Cleveland, Ohio*

## APPLICANTS FOR ASSOCIATE MEMBERSHIP

P. T. Francis, *Port Arthur, Tex.*
Alfred J. Sawyer, *Trenton, Mich.*

## APPLICANTS FOR JUNIOR MEMBERSHIP

Allen E. Abrahams, *Hyattsville, Md.*
David D. Adams, *Schenectady, N. Y.*
Muhammad Ali, *Washington, D. C.*
Philip M. Allen, *Jackson, Mich.*
Eldon D. Arnold, *Morgantown, W. Va.*
Joseph B. Arots, *Wilmington, Del.*
Ben C. Ball, Jr., *Port Arthur, Tex.*
Seymour M. Barer, *Brooklyn, N. Y.*

## COUNCIL'S REPORT

Engineering, Pennsylvania State College and the University of South Carolina, which brings the total number of student chapters at this date to 94.

The Student Chapters Committee has continued with the cooperation of the Council to publish the *Student Chapter News* and more on this subject will appear in the report of the Student Chapters Committee.

In establishing Student membership the Council emphasizes that such membership should in no way affect the membership of student chapters, that is, there should be no thought of limiting student chapter membership to student members.

As to an interpretation of who should be eligible for Student membership the Council passed the following resolution:

> RESOLVED that a student to be eligible for Student Membership must be enrolled in a course leading to a bachelor's degree or advanced degree granted upon the recommendation of a department or division of chemical engineering.

*Student Membership*

The dues for Student membership have been established at $1.00 per year and Student membership, the same as all other grades of membership, is on a calendar year basis. Along with Student membership goes the privilege of subscribing to *Chemical Engineering Progress* at the special price of $3.50.

*Activities with Other Groups*

This is the first year the Institute has been a member of the American Standards Association. We have worked with it in the past closely on the establishment of a Standard System of Symbols and Nomenclature Covering Unit Operations of Chemical Engineering and have during the year joined with other societies through the A. S. A. in the establishment of standard symbols for use on engineering drawings particularly as they apply to the chemical engineering field. T. H. Chilton has been the official representative of the Institute on the Standards Council of the A. S. A. with E. H. Amick as alternate. One of the outstanding activities of the A. S. A. is the Chemical Industry Correlating Committee on which J. C. Lawrence is our representative with M. B. Conviser and W. G. Fogg as alternates. Representing the Institute on other A. S. A. committees are: Crosby Field—Committee B-9, Safety Code for Mechanical Refrigeration; R. S. Roberts—Committee B-31, Standard Code for Pressure Piping; Committee Z10, Letter Symbols and Abbreviations for Science and Engineering—M. Souders, who also represents the Institute on A. S. A. Committee—Z-32, Graphical Symbols and Abbreviations for Use on Drawings; R. C. Stratton—Committee Z-37, Allowable Concentration of Toxic Dusts and Gases; C. G. Shepherd—Committee Z-42, Safety Code for Dry Cleaning Units.

The Institute has continued its participation in Engineers Joint Council which is a joint effort with the American Society of Civil Engineers, American Society of Mechanical Engineers, American Institute of Electrical Engineers and the American

Harold M. Belkin, *Pittsburgh, Pa.*

Joseph H. Bernstein, *New York, N. Y.*

John F. Blumenfeld, *Pittsfield, Mass.*

Niras Kumar Bose, *New York, N. Y.*

Robert S. Boyd, *Pampa, Tex.*

James Brooks, *Somerville, N. J.*

Charles S. Brown, *New York, N. Y.*

James H. Browne, *Boulder, Col.*

George Theodore Bruun, Jr., *Beaver, Pa.*

William Budd, *Cincinnati, Ohio*

Charles A. Burdell, *East Point, Ga.*

Dan C. Campbell, *Niagara Falls, N. Y.*

William A. Carr, *Wilmington, Del.*

Anthony J. Carracino, *Newark, N. J.*

Joseph E. Carvitti, *Bucyrus, Ohio*

George H. Cassedy, *Wilmington, Del.*

V. R. Chari, *Knoxville, Tenn.*

Jerry Cline, *Oleum, Calif.*

Robert M. Cline, *Luckey, Ohio*

Earl Wm. Coderre, Jr., *Westmont (Que.), Canada*

Thomas H. Coffing, *Dayton, Ohio*

Homer D. Coombs, *Institute, W. Va.*

George F. Crewe, *Morgantown, W. Va.*

Gordon G. Cross, *Detroit, Mich.*

Robert F. Curran, *Weymouth, Mass.*

Daniel Leo Daly, *Taft, Calif.*

Edward S. Davis, *Wilmington, Del.*

George A. Doren, *Seattle, Wash.*

John A. Duffie, *Madison, Wis.*

Robert W. Duhl, *Orange, Tex.*

Wendell E. Dunn, Jr., *Baltimore, Md.*

Chris W. Egler, Jr., *Hackensack, N. J.*

Norbert C. Engst, *LaGrange, Ill.*

William Erickson, *Louisville, Ky.*

Nicholas Ermolovich, *Old Forge, Pa.*

Richard W. Eustis, *Fanwood, N. J.*

Clifford Evans, *Seattle, Wash.*

Jack B. Feder, *Brooklyn, N. Y.*

James N. Felger, *Kenmore, N. Y.*

James K. Ferrell, *Raleigh, N. C.*

Neil S. Fussell, *Port Arthur, Tex.*

Frederick W. Gander, *Wilmington, Del.*

Franklyn A. Gardiner, *Huntsville, Ala.*

Raymond A. Gaynes, *Oak Lawn, Ill.*

O. G. Gilbert, Jr., *Detroit, Mich.*

Charles E. Golding, *Odessa, Tex.*

Ted B. Goldmann, *Dallas, Tex.*

Moe M. Goldy, *Newark, N. J.*

A. Grayson Grant, *Penns Grove, N. J.*

G. W. Gray, *Savannah, Ga.*

Harvey J. Grimes, *Norwood, Pa.*

Wallace K. Grubman, *New York, N. Y.*

Jack A. Guthrie, *Marcus Hook, Pa.*

Charles H. Hacker, *Brooklyn, N. Y.*

David W. Hardesty, *Marion, Ohio*

Ernest T. Harper, *New York, N. Y.*

Stanley A. Hauer, *Wilmington, Del.*

Joseph D. Helwig, *Drexel Hill, Pa.*

Elger H. Hemminghaus, *Niagara Falls, N. Y.*

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D. F. Hoffman, *Nitro, W. Va.*

Thomas Keating Holland, *Wilmington, Del.*

Tom Hutson, Jr., *Phillips, Tex.*

Gordon C. Inskeep, *Chicago, Ill.*

J. D. Jay, *Wilmington, Del.*

Charles S. Joanedis, *Wilmington, Del.*

Earl Clare Kallman, *Pico, Calif.*

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James Walter Kay, *Alhambra, Calif.*

Sylvian H. Kernaghan, *Akron, Ohio*

Carl H. Kotheimer, *Lorain, Ohio*

Malcolm J. Knebel, *Fair Haven, N. J.*

Carlos Alberto Knoepffler, *Managua, Nicaragua, C. A.*

Arthur H. Krugler, *Akron, Ohio*

Stanley Lee Krugman, *New York, N. Y.*

Richard D. Lemmerman, *Newington, Conn.*

Albert E. Lewis, *Nitro, W. Va.*

Robert C. Liimatainen, *Chicago, Ill.*

W. Henry Linton, Jr., *Wilmington, Del.*

James M. Madigan, *Cleveland, Ohio*

Russell V. Malo, *Munster, Ind.*

Elmer D. Malone, *St. Louis, Mo.*

Raymond J. Mannella, *Pittsburgh, Pa.*

Carl H. Manwiller, *Wilmington, Del.*

C. H. Marshall, *Baytown, Tex.*

J. C. Martin, *Chicago, Ill.*

James A. Mason, *Rochester, N. Y.*

Robert A. McAllister, *Atlanta, Ga.*

Gordon J. McCarthy, *Alma, Mich.*

John H. McCormick, *Charleston, W. Va.*

Richard P. Medlin, *Beaumont, Tex.*

Paul H. Mehne, *New Castle, Del.*

Alex R. Mitka, *Minneapolis, Minn.*

James F. Mudd, *Louisville, Ky.*

William T. Muncaster, *Woodstown, N. J.*

S. R. Nanavati, *Bombay, India*

Lloyd A. Nelson, *Spokane, Wash.*

Melvin C. Nelson, *Clifton, N. J.*

James R. O'Connor, *Pottstown, Pa.*

Robert O'Ferrall, *Terre Haute, Ind.*

T. M. O'Grady, *Stamford, Conn.*

Wynn W. Oliver, *Santa Cruz, Calif.*

Russell J. Olson, *Fairlawn, N. J.*

Harold W. Ordway, *Brecksville, Ohio*

Kenneth Oringer, *Spring Valley, N. Y.*

Francis O'Shaughnessy, *Woodstown, N. J.*

Robert C. Petrey, *Kingsport, Tenn.*

V. P. Piana, *Borger, Tex.*

Raymond J. Pikna, *Akron, Ohio*

Charles A. Plank, *Raleigh, N. C.*

Arthur J. Prohl, *Hammond, Ind.*

Robert L. Puryear, *Cincinnati, Ohio*

Thomas J. Regan, *Pittsburgh, Pa.*

Alvin E. Ring, *Allston, Mass.*

George W. Ritter, *Whiting, Ind.*

Arnold I. Salka, *Los Angeles, Calif.*

John P. Sanders, *Fayetteville, Ark.*

Donald H. Sartor, *O'Fallon, Ill.*

W. K. Savage, Jr., *Port Arthur, Tex.*

Robert P. Schaaf, *Short Hills, N. J.*

Don B. Schiewetz, *Cincinnati, Ohio*

John J. Sebenick, *Columbus, Ohio*

Ferdinand L. Sedlacek, *Bronx, N. Y.*

Willis J. Service, Jr., *Willow Run, Mich.*

Kamal Abdu Shair, *Ann Arbor, Mich.*

R. B. Shirra, *Redwater (Alta.), Canada*

Lawrence Shprintz, *Philadelphia, Pa.*

Carl D. Spangler, Jr., *Independence, Mo.*

James Edward Springgate, *St. Louis, Mo.*

Maurice E. Stanley, *Port Arthur, Tex.*

William A. Statesir, Jr., *Penns Grove, N. J.*

Ludwig Stern, *Philadelphia, Pa.*

Charles V. Sternling, *Emeryville, Calif.*

J. E. Stevens, *Texas City, Tex.*

Ross D. Stevenson, *Ferndale, Mich.*

Keith G. Steyer, *Berkeley, Calif.*

Edgar A. Stoddard, Jr., *Orono, Me.*

Donald C. Teal, *Buffalo, N. Y.*

Jay M. Tenzer, *Newark, N. J.*

Jonathan I. Thigpen, *Wilmington, Del.*

David W. Thornburg, *Boulder, Col.*

Melvin Tobias, *Oak Ridge, Tenn.*

Herbert L. Toor, *Evanston, Ill.*

James M. Trebilcock, *E. St. Louis, Ill.*

James F. Utley, *Niagara Falls, N. Y.*

Robert G. Vanderwater, *Richland, Wash.*

Theodore J. VanKirk, *Niagara Falls, N. Y.*

Robert R. Voigt, *Warren, Pa.*

Gerard N. Vriens, *Somerville, N. J.*

G. R. Walton, Jr., *Pasadena, Tex.*

W. W. Wamsley, *Seattle, Wash.*

Charles A. Waugaman, *Woburn, Mass.*

Peter F. Way, *New York, N. Y.*

John N. Whelan, *Woodstown, N. J.*

Fred H. Whitaker, *Orange, Tex.*

Douglass White, *Louisville, Ky.*

Harold E. Whitlock, *Wilmington, Del.*

Albert E. Wickland, Jr., *Chicago, Ill.*

Ray H. Wilber, *Wilmington, Del.*

Robert B. Winsbro, *Oak Ridge, Tenn.*

Fred H. Winterkamp, *Orange, Tex.*

Stuart R. Wright, *Arvida (Que.), Canada*

Eugene Yarotsky, *St. Marys, Pa.*

## COUNCIL'S REPORT

Institute of Mining Engineers. Our representation on E. J. C. has consisted of: S. D. Kirkpatrick, as Past President, W. L. McCabe, as President, D. B. Keyes as alternate and S. L. Tyler as Secretary. Other members of the Institute have served as representatives on various committees of E. J. C.; among these are the following: A. G. Aitchison—Committee to Study Cancer Research; N. A. Shepard, General Survey Committee; A. B. Newman, Z. G. Deutsch and N. A. Shepard—International Relations Committee; D. L. Katz—Joint Committee on Student Chapters; A. B. Newman and N. A. Shepard, National Engineers Consultative Committee; R. D. Hoak—Temporary Exploratory Committee on National Water Policy; L. W. Bass —Committee on Unity in the Engineering Profession. The Temporary Exploratory Committee on National Water Policy prepared a comprehensive study and report of the water problems of the nation which was presented to the President's Commission on National Water Policy and members of this committee have cooperated with the President's Commission. The Committee on International Relations has been very active in carrying on negotiations with engineering societies in South America, exploring the possibility of a hemisphere engineering society which would devote itself to the problems common to engineers of the Western Hemisphere. More recently E. J. C. has been requested to advise the National Security Resources Board on an over-all National Manpower Policy covering technically trained personnel. Work on this is in progress at this time and no final report has been submitted. Other groups working in a similar capacity are the National Research Council, American Institute of Physics and American Chemical Society.

The Institute has worked closely with the Engineers' Council for Professional Development, being represented on the Council by C. G. Kirkbride, P. D. V. Manning and W. N. Jones. Institute representatives on E. C. P. D. Committees: Z. G. Deutsch—Committee on Employment Conditions for Engineers; B. F. Dodge—Committee on Engineering Schools; D. B. Keyes—Joint Committee on Professional Training; L. W. Bass—Committee on Principles of Engineering Ethics; E. J. Lyons—Committee on Professional Recognition and Z. G. Deutsch—Committee on Student Selection and Guidance, and also its chairman. The Council approved the Canons of Ethics without superseding our Code of Ethics as it appears in our own Constitution, and further ordered that they be published whenever our Constitution and By-laws are published. The Committee on Professional Training has presented a complete report outlining the recommended procedure and program for E. C. P. D. to cooperate in this field. The Institute has also approved the general idea of E. C. P. D. embarking upon this venture as the program was clear and appeared to be well thought out and well prepared. It is with the Committee on Engineering Schools of E. C. P. D. that the Institute cooperates so fully on matters having to do with accrediting and in all cases the Committee on Engineering Schools and also E. C. P. D. have accepted the recommendations of the Institute's Committee on Chemical Engineering Education and Accrediting.

## COUNCIL'S REPORT

Other groups with which the Institute carries on a rather limited cooperation are: American Documentation Institute through R. S. McBride as representative; American Society of Heating and Ventilating Engineers through J. L. York as a member of the International Joint Committee on Psychrometric Data; American Society of Mechanical Engineers through T. B. Drew on the Heat Transfer Division Coordinating Committee and the Liaison Committee of Process Industries Division and through J. J. Grebe on the Committee on Industrial Instruments and Regulators Division, also, H. F. Newman on the Power Test Codes Committee on Centrifugal and Rotary Pumps; American Society of Refrigerating Engineers through H. C. Duus as representative on the Joint Committee on Rating Refrigerating Equipment; American Society for Engineering Education through A. B. Newman and S. D. Kirkpatrick as representatives of the Committee on Relations with Industry; National Association of Corrosion Engineers through R. B. Mears and M. G. Fontana as our representatives on the Inter-Society of Corrosion Engineers; National Engineering Advisory Committee through A. B. Ray; National Research Council through J. C. Elgin on the Division of Chemistry and Chemical Technology and G. O. Curme on the Division of Engineering and Industrial Research, also on the Conference on Glossary of Terms in Nuclear Science and Technology, J. R. Huffman has acted as our representative with F. J. Van Antwerpen as alternate. On the National Safety Council R. C. Stratton has been our representative with V. R. Croswell as alternate; J. M. Weiss represents the Institute on the Committee on National Bureau of Engineering Registration of the Advisory Board of the National Council of State Boards of Engineering Examiners.

It is with a sense of real loss to the Institute that the Council reports the passing during the year of the following:

*Active Members:* M. J. Bahnsen, W. C. Bainbridge, C. W. Cuno, F. E. Dodge, W. H. Gabeler, A. E. Gibbs, J. M. Graham, Jr., B. A. Irwin, H. M. Kaufman, E. C. Merrill, L. A. Olney, M. Randall, W. F. Washburn, A. H. Winheim, F. J. Wood, R. Woodward, Jr.

*Associate Member:* E. Kihn.

*Junior Members:* S. J. Brill, R. F. Carucci, T. C. Main, B. G. Nelson and E. H. Von Storch.

### AND NOW IT'S OCTOBER

If readers have copies of the October, 1950, issue which have already served their purpose, we shall be glad to pay 50 cents for each one. Send them to Chemical Engineering Progress, 120 East 41st Street, New York 17, N. Y., postpaid. Indicate your name and address plainly on the outside or inside of the package. Do heed this request—we need this issue.

## SECRETARY'S REPORT

THE Council of the Institute met on Sunday, Dec. 3, at the Neil House in Columbus, Ohio. The first order of business after the approval of Minutes was the appointment of personnel of committees for the year 1951. This was completed and will appear as a supplement to the 1950 Year Book and it is expected that the membership will have already received this supplement.

The Council received the report of the Tellers and in accordance with the requirements of the Constitution declared elected the following officers for 1951: President, Thomas H. Chilton; Vice-President, William I. Burt; Treasurer, Carl R. DeLong, and Secretary, Stephen L. Tyler, and the following Directors were declared elected for the period 1951-1953: Charles R. Nelson, Earl P. Stevenson, Robert C. Gunness and R. Paul Kite.

The Council reviewed the report from the Committee on the Future of the Institute, L. W. Bass, chairman, which resulted in a continuance of the committee and an appreciable enlargement, and as Dr. Bass felt that he could not carry on as chairman W. T. Nichols was appointed as chairman with L. W. Bass, J. L. Bennett, G. G. Brown, W. I. Burt, F. J. Curtis and M. C. Molstad as members of the committee.

There was considerable discussion on the question of Student Membership, particularly as to those students who should be considered eligible for such grade of membership. It was therefore voted that the resolution passed at the Nov. 10 meeting (C.E.P., December, 1950, page 26) be amended to read as follows:

RESOLVED that a student to be eligible for Student Membership must be enrolled in a course leading to a bachelor's degree or advanced degree granted upon the recommendation of a department or division of chemical engineering providing he is taking instructions equivalent to one-third the credit requirements in a regular full-time curriculum.

The budget for the Institute for the year, 1951, was submitted and after considerable discussion was approved; also the budget for Chemical Engineering Progress was approved at the same time.

J. C. Elgin, as chairman of the Constitution and By-Laws Committee reported that considerable progress was being made in the preparation of a new set of bylaws and it was voted that a draft be prepared for submission to Council at as early a date as possible.

## A YOUNG ENGINEER

It seems that the employer-employee relationship under which most engineers work has tended to lessen the *time* which engineers have available for such important professional considerations. Also has this relationship lessened the *likelihood* of the engineer's making these considerations since a problem can seem ideally solved by the employer before any such consideration of consequences enters the question. I do not believe that engineers in general will be publicly recognized as professionals until they take it upon themselves, in spite of their handicaps, to become a group dedicated to public service, by the means outlined here. Better minds than mine have said similar things many times before (recently *1-4, 6, 7, 10, 11, 14, 16, 18-20, 23-26, 28, 31-33*), but until this exhortation is reflected in accomplishment, I must admit, after ten years of preparation and work in engineering, disappointment with the attainments of this vocation.

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CLEAN

U.S. *Sanitary* MOTOR

## SECRETARY'S REPORT

The December meeting of the Executive Committee was held on the 15 at the Offices of the Institute. The Treasurer's report and bills were received and approved. The applicants for membership whose names appeared in the November, 1950, issue of *Chemical Engineering Progress* were elected to the grades of membership indicated.

F. J. Lockhart was appointed counselor of the student chapter at the University of Southern California to succeed F. A. Landee. R. N. Maddox was appointed counselor of the student chapter at Oklahoma A. & M. College to succeed W. A. Klemm.

The following members have entered the Armed Forces of the country and are therefore placed on the Suspense List which provides for a continuation of their membership without financial obligation up to a period of six months beyond the termination of their service: Albert Edwards, John J. Foster, H. A. Golle, Joseph Novack and Robert R. Rhodes.

Resignations were accepted from twelve members.

T. H. Chilton was appointed representative of the Institute to attend the Ceremonial Session of the American Chemical Society in celebration of its Seventy-Fifth Anniversary.

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The Executive Committee met Jan. 12, 1951, just preceding the meeting of Council, and after approving minutes, Treasurer's report and bills, proceeded with the other business of the meeting. Those applicants whose names were listed in *Chemical Engineering Progress*, December, 1950, were elected to the grades of membership as indicated.

The appointment of committee personnel for 1951 was completed and reappointments made in the limited number of cases where members found it impossible to serve.

Resignations were accepted from 14 members. The following members have entered the Armed Forces and are therefore placed on the Suspense List for the period of their Service and six months after discharge from the Service: J. M. Jacobs and P. W. Riegelhaupt.

James C. Lawrence was appointed Institute representative on a special committee of the American Standards Association to study a Proposed Project on Storage and Handling of Anhydrous Ammonia and Ammonia Solutions.

# TECHNICAL PROGRAM

## WHITE SULPHUR SPRINGS MEETING

### Symposium: The Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment

**Monday, March 12, 1951**

**Morning Sessions beginning at 9:15 A.M.**

*Walter E. Lobo, presiding*

Applications of Fluid Mechanics and Similitude to Scale-Up Problems.—*J. H. Rushton*

Relationship Between Test Data and Industrial Plant Equipment.—*Paul Talmey, Gregoire Gutzeit and J. Robert Sproul*

**Afternoon Sessions beginning at 2 P.M.**

*Walter E. Lobo, presiding*

Interpreting Small Scale Filtration Tests in Terms of Commercial Scale Equipment.—*J. A. Kenney*

Practical Evaluation of Pilot Plant Filtration Data.—*R. N. Hill and M. M. Kaiser*

**Tuesday, March 13, 1951**

**Morning Sessions beginning at 9:30 A.M.**

*J. R. Kernan, presiding*

The Relation of Pilot Plant Operation to Commercial Plant Operation in Selective Energy Absorption Freeze Drying.—*A. G. Blank and William H. Zamzow*

The Evaluation of Centrifuge Performance.—*Charles M. Ambler*

**Afternoon Sessions beginning at 2 P.M.**

*J. R. Kernan, presiding*

Scale-Up of Semi-Works Distillation Equipment.—*J. B. Jones and Cyrus Pyle*

**Wednesday, March 14, 1951**

**Morning Sessions beginning at 9:30 A.M.**

*G. T. Skaperdas, presiding*

The Design of Commercial Continuous Reactor Systems From Pilot Plant Batch Data.—*Arthur P. Weber*

A Procedure for Scaling-Up a Catalytic Reactor.—*John Beek, Jr., and Emanuel Singer*

## NEWS

### A.S.A. ABBREVIATIONS FOR DRAWINGS READY

A revised edition of the American Standard Abbreviations for Use on Drawings was recently published by the American Standards Association, 70 East 45th Street, New York, N. Y.

To bring the 1946 edition of the standard up to date with latest industry-wide practice a committee representing technical associations, industry, government and independent experts developed this edition. It will aid draftsmen, shopmen, assemblers, and construction men in interpreting industrial drawings done by various companies and branches of the government. More than 200 changes have been made in the abbreviations included in the original edition, and more than 40 new abbreviations have now been incorporated.

Copies of the American Standard Abbreviations for Use on Drawings, Z32.13-1950, may be obtained at $1.00 per copy.

### INSTRUMENTAL ANALYSIS COURSES AT M.I.T.

Two one-week specialized training programs in instrumental analysis will be offered as part of the 1951 summer session at M.I.T., Cambridge, from July 9-13 and July 16-20.

In announcing the two courses, Prof. W. H. Gale, director of the M.I.T. summer session, emphasized the increased use of instrumental methods in applied analytical chemistry. The first week's program will be devoted to electrical methods of instrumental analysis and the second will cover optical spectrophotometry, colorimetry, etc. Both programs will consist of a two-hour laboratory workshop period for lecture and discussion and a three-hour laboratory workshop each day.

## TEL. PLANT EXPANDS DU PONT'S FACILITIES

A new continuous process for the manufacture of tetraethyl lead, a gasoline additive essential to the nation's modern fighting power, has been perfected by Du Pont research men and engineers. The company announced that construction will start immediately on the first new continuous production unit which will have an annual production capacity of about 50 million pounds of tetraethyl lead a year. This expansion of tetraethyl lead facilities will substantially increase Du Pont's ability to meet the heavy demand for high octane fuel.

At the present time, tetraethyl lead is made in batches, a process perfected by Du Pont as early as 1923. In addition to increasing productive output, the new continuous process eliminates the need for equipment made of special steel alloys which are essential in the batch process. The new process is the result of advanced engineering design, and a major change in the basic chemical process.

The continuous process tetraethyl lead plant will be located at the Du Pont Co.'s Chambers Works at Deepwater Point, N. J. It is expected to be in production by January, 1952. Contracts have already been given out for both materials of construction and manufacture.

Sodium to supply the needs of this expanded tetraethyl lead production will be furnished in part by the adoption of a new process now being installed at Memphis, Tenn., for production of sodium cyanide from hydrogen cyanide and caustic. Sodium cyanide is currently being produced by a process requiring metallic sodium. Upon completion of the Memphis plant by Jan. 1, 1952, this sodium will be available for tetraethyl lead production.

## CANADIAN AWARD TO BE OFFERED

The award of a palladium medal for outstanding contribution to the science of chemistry or chemical engineering will be one of the principal features of the 34th annual conference of The Chemical Institute of Canada, scheduled for Winnipeg, June 18-20, 1951. This award will be known as The Chemical Institute of Canada Medal and will be the highest honor that the Institute can give to a chemist or chemical engineer.

The medal was offered to the Institute through the International Nickel Co. of Canada Ltd. who wished to commemorate the 200th anniversary of the separation of nickel by the Swedish chemist Cronstedt.

# LOCAL SECTION

## ROCHESTER

The meeting on Jan. 17 consisted of an inspection tour of the R. G. & E.'s Russell Station, followed by an address by Alexander Beebe, president of Rochester Gas & Electric Corp. It was designed to give members an opportunity to become better acquainted with the private operation of a public utility company.

Mr. Beebe presented a picture of the private operator's opinions on government-operated projects before 75 members and guests. He stated they were in agreement with government operation in areas where power was needed, but the economics made it impractical for private companies to operate. However, he was emphatic in stating that government should not go beyond this.

*Reported by O. J. Britton*

## AKRON

At the Jan. 11 meeting held at the University Club, 80 members and guests attended. Robert Hampton of the Akron Better Business Bureau gave a brief talk on the history of the BBB demonstrating how that organization serves and helps the housewife save money.

H. F. Livingston, manager, public relations department, Du Pont Co., spoke on "Progress in Better Living." He gave his listeners a preview of chemical developments of the future and also demonstrated a new man-made fiber known as Orlon acrylic fiber. He pointed out that it takes many years to develop a new material and stated that the development of nylon illustrates the story of American industrial success, "which means the cooperation between research, the investor, labor and management."

The 1951 treasurer of the section is Leonard A. Harris and not William Harlacher as first reported.

*Reported by Edmund Duplaga*

## MARYLAND

The annual business meeting was held Dec. 12, 1950, at Johns Hopkins University at which the following officers were elected for 1951:

Chairman...............F. C. Dehler
Vice-Chairman..........L. J. Trostel
Secretary-Treasurer..Alan Beerbower

The meeting was addressed by G. E. Mullin of Dowell Inc. He discussed "Combating Corrosion with Metal from the Sea."

*Reported by Alan Beerbower*

## FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

*Chairman of the A.I.Ch.E. Program Committee*

Walter E. Lobo

The M. W. Kellogg Co.,

225 Broadway, New York 7, N. Y.

### MEETINGS

White Sulphur Springs, W. Va., The Greenbrier, March 11-14, 1951.
*Technical Program Chairman:* Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

Kansas City, Mo., Hotel President, May 13-16. 1951.
*Technical Program Chairman:* Walter W. Deschner, J. F. Pritchard Co., Kansas City, Mo.

Rochester, N. Y., Sheraton Hotel, Sept. 16-19. 1951.
*Technical Program Chairman:* D. E. Pierce, General Aniline & Film Corp., 230 Park Ave., New York, N. Y.

Annual — Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.
*Technical Program Chairman:* Frank J. Smith, Pan American Corp., New York, N. Y.

French Lick, Ind., French Lick Springs Hotel, May 11-14, 1952.
*Technical Program Chairman:* W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.

### SYMPOSIA

**Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment**
*Chairman:* Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.
*Meeting*—White Sulphur Springs, W. Va.

**Maintenance**
*Chairman:* D. E. Pierce, General Aniline & Film Corp., 230 Park Ave., New York, N. Y.
*Meeting*—Rochester, N. Y.

**Industrial Applications of Photography**
*Chairman:* Carl Gath, Eastman Kodak Co., Kodak Park Works, Rochester, N. Y.
*Meeting*—Rochester, N. Y.

**Vacuum Engineering**
*Chairman:* W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.
*Meeting*—French Lick, Ind.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, Walter E. Lobo, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 70 days before a meeting cannot be considered.

## KNOXVILLE-OAK RIDGE

Officers elected for 1951 are as follows:

Chairman..............A. C. Jealous
Chairman-elect...W. B. Harrison, III
Secretary..............F. N. Browder
Treasurer..........W. K. Stromquist
Asst. Secretary........H. F. Johnson
Directors......H. J. Garber, J. A. Lane, and G. H. Montillon

*Reported by F. S. Chance, Jr.*

## TENNESSEE VALLEY

The following officers have been elected for 1951:

Chairman................L. F. Roy
Vice-Chairman........W. C. Saeman
Secretary.............W. L. Darrow
Treasurer.............Tom Mitchell
Executive Committee...Herbert Kerr and Nathan Gilbert

*Reported by Cecil Rose*

## CHARLESTON, W. VA.

A general meeting of this section was held at the Charleston Recreation Center Jan. 16, 1951; about 110 members and guests were present.

The speaker of the evening was Paul J. Culhane of the patent division of the Du Pont Co.'s legal department. His subject was "What a Chemical Engineer Should Know About Patent Procedure." Dr. Culhane opened his remarks with definitions and descriptions of what is patentable. He pointed out how judges and examiners differ in interpretations of the words—inventive, unobvious, beneficial, etc.

The speaker outlined the necessary steps in making a patent application. The speaker also stated that the use of patents is increasing; that a product or process cannot really be kept secret unless the organization is very small. He further thought that recent court rulings had not damaged the patent structure.

The meeting closed with a question period.

*Reported by M. C. Guthrie, Jr.*

## SOUTHERN CALIFORNIA

This section held its monthly dinner meeting Jan. 16, at Scully's Cafe in Los Angeles. Some 55 members and guests were present to see the technicolor motion picture film, "The Story of Palomar," which was presented by S. B. Nicholson and Robert Richardson, members of the staff of the astrophysics department, California Institute of Technology. Slides were also shown in conjunction with a discussion of studies and objectives of some of the programs currently under way at the observatory. The film was of interest to southern Californians, since it portrayed the growth of the 200-in. mirror from its casting through the precise grinding, polishing and testing to the final installation at Mount Palomar.

*Reported by G. S. Peterson*

## COASTAL GEORGIA CHEMICAL ENGINEERS CLUB

At the Nov. 17, 1950, meeting held at the DeSoto Hotel in Savannah, fifty-nine persons heard C. E. Tyler, chief chemist of the Brunswick plant, Hercules Powder Co., give a talk on "Rosin, Chemistry and Sources."

A meeting was scheduled for Feb. 9, 1951, in Brunswick, Ga. The speaker, C. A. Higgins, president of Hercules Powder Co., chose as his subject "The Chemical Engineer and the War Emergency."

*Reported by E. O. Barnes*

# RUST FORMATION ON 18-8 STAINLESS STEEL

*NORMAN S. MOTT*
*Chief Chemist and Metallurgist*

The popular conception that rust can never form on 18-8 stainless steel unless something is wrong with the chemical composition or the heat treatment, is a long way from the truth. Experience has shown that rust can occur on stainless alloys of controlled composition and heat treatment as the result of surface contamination. Among the many sources of contamination which may contribute to the formation of rust on the surface of stainless steels, the following are leading offenders:

1. An iron film left on the surface as the result of a machining or other manufacturing operation will tend to rust in the presence of moisture.

2. Microscopic scale particles left on the surface after pickling may become visible as "rust" under suitable conditions.

3. Pickling solution oozing from minute pores in the metal may stain the surface and oxidize to a brown rust color due to the iron which it contains.

4. The accumulation of the natural corrosion products of the alloy in corrosive service on a rough surface may cause a brown stain due to oxidation.

5. Discoloration may be caused by the accumulation of any extraneous processing material which is of such a nature as to cause a "rusty" appearance on a rough surface.

Articles that are to have a truly "stainless" appearance should have all scale completely removed by suitable cleaning methods, should be passivated after machining operations in warm dilute nitric acid, should be free from porosity, and should have a reasonably smooth surface.

A smooth or polished surface will always stay cleaner and brighter, and be more resistant under mildly corrosive conditions than a rough surface and this tendency increases with the degree of polish. Although it is true that stainless steel is at its best when highly polished, it should be remembered that under strongly corrosive conditions this polish is soon removed. For most applications, it is the inherent resistance of the alloy that counts and "rust" conditions such as those described are relatively harmless. They are the results of surface contamination and in no way reflect the composition of the alloy or the effectiveness of the heat treatment.

## SOUTH TEXAS

This section met Jan. 19 at the Pasa-
dena plant of the Champion Paper and
Fiber Co. for an inspection of their
paper and pulp plant. At the meeting
which followed approximately 65 mem-
bers of the local section heard Messrs.
R. L. Betts and J. H. Moyer of Cham-
pion speak on the subject "Paper in the
Making."

Both speakers are graduates of the
Pulp and Paper School of Syracuse
University and have had industrial ex-
perience in the technical aspects of paper
manufacture.

The December, 1950, meeting of this
section featured an inspection trip
through the Houston plant of the Na-
tional Biscuit Co. At the meeting which
followed, Ralph R. Browning spoke on
the topic, "A Catalyst of Industrial
Progress." Mr. Browning's talk con-
cerned the patent system of the United
States.

Also at the December meeting an-
nouncement was made of the selection of
the new officers for 1951. These officers
are as follows:

Chairman—W. E. Alexander, Mon-
santo Chemical Co.
Chairman - Elect—C. L. Dickinson,
Diamond Alkali Co.
Secretary—H. D. Foster, Du Pont Co.
Treasurer—W. W. McLean, Carbide
& Carbon
Executive Committee—M. C. Hopkins,
J. A. Lee, and W. T. Richard

The section met Nov. 17, 1950, at
the Houston plant of the A. O. Smith
Corp. for an inspection of the manufac-
turing processes on pressure vessels,
propane and butane systems, and deep
well pumps. At the meeting which fol-
lowed, Prof. J. H. Rushton, Ill. Inst. of
Tech., discussed, "Scale-up of Pilot
Plant Operations Involving Liquid-Gas
Interfaces."

*Reported by Guy T. McBride, Jr.,*
*and Henry D. Foster*

## OHIO VALLEY

This section will have an inspection
trip to Armco Steel Corp., Hamilton,
Ohio, at 7:30 P.M., Feb. 21, 1951.

A joint Chemical Engineering Sym-
posium meeting was held Jan. 31, with
the American Chemical Society at the
Herman Schneider Foundation Building
in Cincinnati. Jacob Cholak, associate
professor of industrial health at the
Kettering Laboratory, University of
Cincinnati, gave a talk on "Instrumental
Methods of Chemical Analysis" during
the first hour. John G. Dobson of the
Foxboro Co. gave a talk on "Instru-
mentation of Processing Equipment"
during the second hour. The symposium
was followed by a social hour sponsored
by Emery Industries, Inc., with Mr.
Alex Brown presiding.

*Reported by Robert W. Evans*

## PITTSBURGH

"The Silicone Story"—the practical
applications and possibilities of commer-
cial silicone products—was described by
James W. Raynolds, assistant manager
of the chemical department, General
Electric Co., to members of this section
at the Jan. 3 dinner meeting held at the
College Club.

High- and low-temperature perfor-
mance, "release" properties, inertness,
and unusual surface properties are the
outstanding attributes of the silicone
family—available as liquids, semi-solids,
grease-like compounds, rubbery solids
and resins. Large- and small-volume
commercial applications were demon-
strated by the speaker, who had on hand
exhibits and special products.

*Reported by Hugh L. Kellner*

## CHEMICAL ENGINEERS CLUB OF WASHINGTON

A public symposium on man's battle
against natural pests was the feature of
the Nov. 13, 1950, meeting of this club.
This was the first meeting of the club
after its recognition as a local section
of A.I.Ch.E.

The meeting was attended by about
150 people. Dr. Sievert A. Rohwer, of
the Department of Agriculture, was
moderator. Dr. S. S. Sharp, entomolo-
gist of the Du Pont Co., described ad-
vances in new insecticides. Dr. P. D.
Peterson, of the Stauffer Chemical Co.,
discussed recent advances in fungicides,
and W. W. Allen, Dow Chemical Co.,
covered new developments in herbicides.

*Reported by D. P. Herron*

## PHILADELPHIA-WILMINGTON

The third meeting of the 1950-51 sea-
son was held at the Clubhouse Hotel,
Chester, Pa., Jan. 9. The speaker of the
evening was Thomas Kennedy, assistant
to the president of Atlas Powder Co.
He emphasized in his talk the impor-
tance of and the need for continued ex-
pansion of the use of scientific methods
in problems dealing with industrial rela-
tions.

The dinner was attended by 83 mem-
bers and guests, and approximately 130
were present for the meeting that fol-
lowed.

*Reported by William E. Osborn*

## BATON ROUGE

Officers elected for 1951 are as fol-
lows:

Chairman............T. M. Smylie, Jr.
Vice-Chairman..........J. E. Moise
Secretary..............J. C. Fedoruk
Treasurer................R. H. Bretz
Executive Committee..D. F. Edwards,
J. B. Killgore, A. Smith, III,
and A. G. Keller

*Reported by J. C. Fedoruk*

## CHICAGO

This section met Jan. 17 in the Western Society of Engineers' suite with about 110 present for the business and technical session.

Guy Reed, known as chairman of the Chicago Crime Commission, talked on "Wartime Economy." His remarks were cogent and informative, and ranged freely over matters of world economy and politics.

On Jan. 8, K. M. Watson made the opening address, "Catalytic Reactor Design," before the newly formed Catalysis Club of Chicago.

*Reported by Thorpe Dresser*

## TULSA

Officers for 1951 are as follows:

*Chairman*—E. C. Carlson, Tulsa
*Vice-Chairman*—Al Morrey, Sand Springs
*Sec'y-Treasurer*—H. S. Wood, Tulsa

At the December meeting of this section Harold Wood talked on "Chicago Industrial Area" and Carl Minden on "Radar Applications." At the last-mentioned 16 were present. At the November meeting 21 were present to hear Remington Rogers talk on "The Trend of Federal Control in Industry."

*Reported by Clifton Frye*

## ST. LOUIS

This section held a highly successful "Old Timers' Night" Jan. 16 at the Missouri Athletic Club. L. E. Stout, dean of engineering at Washington University, called attention to the fact that much of the chemical engineering department's growth has resulted from a close cooperation between the University and St. Louis industry which has resulted in benefits to both.

Carroll A. Hochwalt, vice-president of Monsanto Chemical Co., spoke to the gathering about "Synthetic Fibers." He quoted some significant figures showing how synthetic fibers are supplying a larger portion of the total textile demand. Reasons for the advance of synthetic fibers are several, he claimed. Properties of these fibers can be more closely controlled and many of the defects of natural fibers can be corrected. Dr. Hochwalt then discussed the production, properties and uses of synthetic fibers. Samples of cloth made from these fibers were circulated through the audience.

The attendance at the dinner which preceded the talk numbered 136 and 54 came in later to hear the lecture.

At the Dec. 19, 1950, meeting held at the York Hotel, R. F. Davis, of the Universal Oil Products Co., discussed,
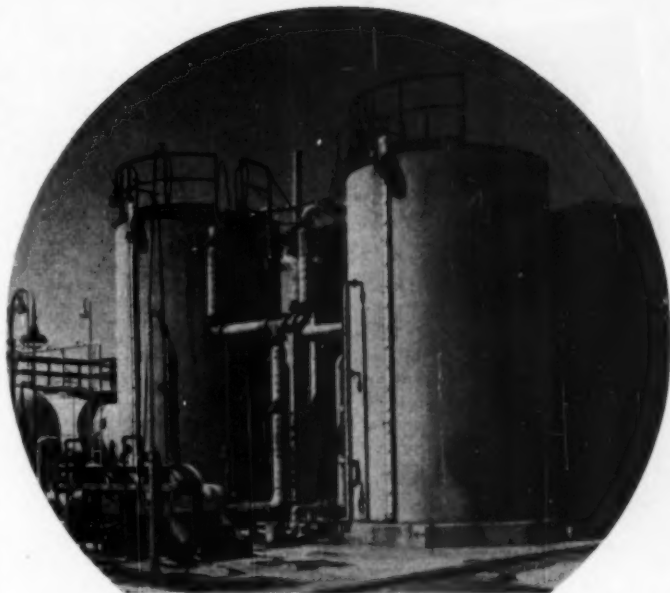


# How SHELL protects glycerine from contamination

The Shell Chemical Corporation is manufacturing glycerine by a synthetic process at its plant in Houston, Texas. There were two problems associated with the intermediate storage of the product. *First*, it was essential that the glycerine *not* be contaminated by metallic corrosion during storage. *Second*, the temperature of the glycerine had to be maintained.

Shell solved the first problem by having us fabricate the tanks out of nickel-clad steel. The second problem was solved by insulating the tanks with magnesia.

The two tanks, which are built in our Birmingham plant, are of butt-welded construction. They are smooth, easy to insulate and have no rough edges where corrosion can start.

Nickel is only one of several corrosion-resistant alloys that we know how to handle. We also fabricate and erect structures made from:

- **CLAD STEELS**—Chrome-nickel or straight chrome stainless, or monel.
- **LININGS**—Chrome-nickel, straight chrome or ELC (extra low carbon) stainless steel, monel or everdur.
- **SOLID CORROSION-RESISTANT METALS**—Chrome nickel or straight chrome or ELC stainless steel, monel, aluminum or everdur.

*We also can supply storage tanks and other equipment made of plain carbon steel. Write our nearest office for estimates or quotations.*

## LOCAL SECTION NEWS

"The Engineer in the Oil Industry." He gave a complete sketch of the petroleum industry from oil well to the gasoline engine concluding with an imaginary trip through a refinery for a look at primary fractination, cracking, and catalytic cracking processes.

*Reported by A. T. Pickens*

### DETROIT JUNIOR GROUP

This group held its regular monthly meeting Jan. 8, 1951, in the Junior Room of Rackham Memorial.

Julian E. Oyaas, research microbiologist in the research department of Parke, Davis and Co., presented a talk entitled, "Microorganisms—The Original Chemical Engineers."

*Reported by W. W. Jones*

### TERRE HAUTE CHEMICAL ENGINEERS CLUB

This club was addressed Jan. 16, 1951, by R. K. Horton, engineer, Ohio River Valley Sanitation Commission who spoke on "Pollution Abatement in the Wabash Valley." Mr. Horton described the activities of the Commission, and presented the results of a recent survey of the Wabash River from Terre Haute to Mt. Carmel, Ind.; he discussed the pollution load measurements and the recommendations made for the amount of treatment required to return the Wabash River to an unpolluted state.

On Nov. 7, 1950, this newly formed club of Terre Haute, Ind., was addressed by W. T. Nichols, director of general engineering, Monsanto Chemical Co., and a Director of A.I.Ch.E., on the subject "The Work of the Institute." In his address Mr. Nichols presented the club with an insight into the work and purpose of the Institute and made recommendations for maintaining an active and stimulating local organization.

A meeting was scheduled for Feb. 8, in the Seminar Room, Commercial Solvents Corp., Terre Haute. Guest speaker D. P. Barnard, research coordinator, Standard Oil Co., has the subject "The Principal Fuel Problems." Membership in the club totals 81. Approximately 50 members attended each of the last two meetings.

*Reported by E. J. Massaglia*

### TWIN CITY

This Twin City section held a dinner meeting at Freddie's Cafe in Minneapolis Jan. 18. After the business meeting a panel discussion was held on "Use of Punch Cards for Technical Information." The panel consisted of:

Margaret Hilligan, General Mills
Esther Aune, Minneapolis, Honeywell
Dr. Karl Heumann, Minneapolis Mining & Manufacturing

Officers elected for the new year are:

*Chairman:* Fred Wehmer, Minnesota Mining & Manufacturing Co.
*Vice-Chairman:* J. B. Calva, J. B. Calva & Co.
*Secretary-Treasurer:* Russell H. Fredrickson, Minnesota Mining & Manufacturing Co.
*Executive Committee:* Walter E. Carlson, General Mills; Robert J. Foster, General Mills; Donald R. Guthrie, Minnesota Mining & Manufacturing Co.; Ralph E. Montonna, University of Minnesota

*Reported by W. M. Podas*

### NEW YORK

This section met Jan. 30 at the Brass Rail Restaurant at noon to hear G. C. Thrift, eastern representative of Koch Engineering Co., Inc., of Wichita, Kan., talk on "Kaskade Trays" in their relation to conventional bubble trays. He presented data showing operating characteristics of several-type installations for absorption, fractionation, and liquid-liquid extraction. His talk was illustrated with numerous slides showing both construction features and operating characteristics.

Skip Thrift, as he is popularly known, is a Texas A. and M. graduate and has spent 20 years of his professional life with one of the major oil companies in engineering design, construction and operation of refineries in the United States and Europe.

*Reported by L. C. Johnston*

## LOCAL SECTION CALENDAR

# PEOPLE

## R. LINDLEY MURRAY
## PRESIDENT OF HOOKER

R. Lindley Murray, formerly executive vice-president of the Hooker Electrochemical Co., Niagara Falls, N. Y., was recently elected president by the board of directors. He is at present a Director of the American Institute of Chemical Engineers, having been elected to that position in 1949 for a three-year period.

Mr. Murray has been associated with the Hooker concern since 1916. He has been a director since 1937 and is also a vice-president and director of Hooker Detrex.

**R. L. MURRAY**

Mr. Murray is a member of many technical societies including the American Chemical Society, Society of Chemical Industry, Electrochemical Society and is a member of the Panel of Arbiters of the American Arbitration Society. He won the Schoellkopf medal for 1949.

**Frederick E. Herstein** has been appointed sales representative in northern New Jersey and parts of New York State for the Glascote Products, Inc. Mr. Herstein graduated from the Polytechnic Institute of Brooklyn in chemical engineering in 1936 and has been active in the corrosion resistant chemical equipment field continuously since that time serving several Eastern concerns in development, production and design capacities.

**J. Rex Adams** formerly technical director, Stein Hall & Co., New York, N. Y., will be employed after March 1 by Old Colony Envelope Co., Westfield, Mass.

**D. D. Margules,** formerly resident engineer, The Lummus Co., Ltd., London, England, is now located at the company's offices in New York.

**Jerome Alexander,** consulting chemist and chemical engineer, New York, N. Y., was made an honorary member of the American Institute of Chemists at the Jan. 25, 1951, meeting of the New York Chapter held at the Hotel Commodore.

Dr. Alexander is internationally known as an expositor of colloid chemistry. He has edited and written many volumes and articles, some of which have become standard textbooks and reference works. Besides being a member of many scientific and honorary societies, he was awarded the Townsend Harris Medal and was decorated by the French Government as Chevalier of the Legion of Honor and as Officer of Public Instruction.

From 1917 to 1919 he was chairman of the National Research Council's subcommittee on glue and other colloids. He is a licensed professional engineer in the State of New York. For 25 years he was treasurer and chief chemist of several associated manufacturing companies. His book, "Life—Its Nature and Origin," (1948) was a development of his Master's thesis written 50 years earlier. He is a charter member of A.I.Ch.E.

## PAINE A FELLOW OF N. Y. ACADEMY OF SCIENCES

Harold W. Paine, assistant to the general laboratory director of Du Pont Co.'s polychemicals department, has been elected to fellowship in the New York Academy of Sciences.

In 1941, Mr. Paine was made a Fellow of the American Association for the Advancement of Science. He was graduated from Brown University in 1907 with a Ph.B. degree and from the Massachusetts Institute of Technology two years later with a B.S. degree in chemical engineering. He was director of Du Pont's plastics research laboratories at Arlington, N. J., for 12 years and took his present position when this activity was shifted to the Experimental Station at Wilmington following the formation of the polychemicals department.

**John L. Davenport,** executive vice-president of the Charles Pfizer & Co., Inc., is serving as chairman of the chemicals division of the Brooklyn Red Cross 1951 Fund Drive. Mr. Davenport is one of approximately 50 Brooklyn, New York, businessmen taking an active role in the Red Cross Campaign which gets under way March 1.

## M. C. WHITAKER HONORED

Milton C. Whitaker, who founded Columbia University's department of chemical engineering and was at one time its head, received that university's Chandler Medal for 1950 in recognition of his achievements in the chemical industry. The award was made Jan. 16. The Chandler medals and lectures were established in 1910 the year that Dr. Whitaker became professor of chemical engineering.

Dr. Whitaker who received his education at the University of Colorado and the University of Pittsburgh, became an instructor in applied chemistry at the University of Colorado and later went to Columbia in a similar capacity. Later he organized the department of chemical engineering. He resigned from Columbia in 1916 and served as vice-president of U. S. Industrial Alcohol Co. in charge of research and production until 1927, and was simultaneously president of U. S. Chemical Co., a subsidiary. In 1930 he joined American Cyanamid Co., as vice-president and director and served in this double capacity until his retirement in 1947.

Last year Dr. Whitaker, now 80 years old, received the Columbia University Medal for Excellence.

**Monte C. Throdahl,** who has served for the past two years in a liaison capacity for the Monsanto Chemical Co., between Nitro (W. Va.) research and the rubber service department sales office at Akron, Ohio, has been appointed assistant director of research. Mr. Throdahl joined Monsanto at Nitro in 1941 as a control chemist in the research department. He had received his B.S. in chemical engineering from Iowa State College. In 1946 he became a research group leader and in May, 1950, was made research supervisor for rubber chemicals.

**John L. Galt** has been appointed manufacturing engineer of the General Electric chemical department's chemicals division phenolic products plant. In this capacity, Mr. Galt has responsibility for the supervision of process engineering, plant engineering, and quality control in the manufacture of magnesium oxide, resins, varnishes, and molding compounds in Pittsfield and varnishes at the Coshocton (Ohio) plant. Having started with the General Electric Co. in 1947, Mr. Galt has been a process development engineer for the past three years.

**C. M. Dennis** recently left the Swenson Evaporator Co., Harvey, Ill., and is now located at 420 Lexington Ave., New York, N. Y., as a consulting engineer in care of Singmaster and Breyer.

## TAYLOR IN FACULTY CHANGE AT PRINCETON

Hugh Stott Taylor, who has asked to be relieved of the chairmanship of the department of chemistry of Princeton (N. J.) University, a position he has held for 25 years, will continue as dean of the Princeton Graduate School. This relinquishment was occasioned by the increasing duties at the Graduate School intensified by the defense program. He will devote much of his time to the development of the program in chemical kinetics at the new James Forrestal Research Center which the university is establishing on an 800-acre tract recently acquired from the Rockefeller Institute for Medical Research. Dean Taylor was recently elected president of the Society of Sigma Xi, a national organization to encourage scientific research.

**Joseph J. Moder, Jr.,** associate professor of industrial engineering at Georgia Tech, has been appointed faculty research associate professor of the Georgia Tech Engineering Experiment Station. Dr. Moder is teaching statistical quality control courses in the Georgia Tech school of industrial engineering and also making an industrial engineering survey of the peanut-shelling plants in Georgia for the Georgia Tech Engineering Experiment Station.

A 1947 Washington University graduate in chemical engineering, Dr. Moder received his doctorate in chemical engineering from Northwestern University. During the war he participated in the Navy's electronics technician program and served as an electronics technician 3/c in the Atlantic theater. In the summer of 1947, Dr. Moder was employed as research chemical engineer by the Petrolite Co., Kilgore, Tex., where he worked on the air-oxidation of petroleum waxes.

**Wesley T. Dorsheimer,** sales engineer, has been transferred from the home office staff of the Foxboro Co., Foxboro, Mass., to the New York office, at 420 Lexington Avenue. Mr. Dorsheimer, a chemical engineer and graduate of Carnegie Tech, served in the Navy as an engineering officer during World War II. Prior to that he was with the Standard Oil Co. of New Jersey, and following the close of the war he was a sales engineer on the New York staff of C. F. Braun & Co. For the past two years he has been at Foxboro, as assistant manager of sales in the chemical industry division.

**A. Garrett Hill** is now technical director, chemicals department, American Cyanamid Co., Bound Brook, N. J.

# CLASSIFIED SECTION

Advertisements in the Classified Section of Chemical Engineering Progress are payable in advance, and are placed at 15c a word, with a minimum of four lines accepted. Box number counts as two words. Advertisements average about six words a line. Members of the American Institute of Chemical Engineers in good standing are allowed one six-line insertion free of charge per year. More than one insertion to members will be made at half rates. In using the Classified Section of Chemical Engineering Progress it is agreed by prospective employers and employees that all communications will be acknowledged, and the service is made available on that condition. Boxed advertisements one-inch deep are available at $15 an insertion. Size of type may be specified by advertiser. In answering advertisements all box numbers should be addressed care of Chemical Engineering Progress, Classified Section, 120 East 41st Street, New York 17, N. Y. Telephone ORegon 9-1560. Advertisements for this section should be in the editorial offices the 20th of the month preceding the issue in which it is to appear.

## SITUATIONS OPEN

### Chemical Process Engineers

Qualified to prepare engineering studies and detailed process designs for petroleum and chemical fluid process plants. Salaried position; location in Boston. In reply please state education qualifications, work experience, and salary desired. Present employers will not be contacted before personal interview. Stone & Webster Engineering Corporation, 49 Federal St., Boston 7, Mass.

### CHEMICAL ENGINEER
#### Experienced

Position of responsibility for production supervision in large and well-established chemical company. Experience should be in, or applicable to, manufacture of re-agent and fine chemicals. Excellent opportunity for right man. Location at start, metropolitan New York but may involve other sections later. Reply, giving complete details of training, experience, personal data and salary requirements. Write Box CP 1353, 221 W. 41 St., NYC.

Head of Classifying and Filing Section in Technical Information Division of Research Laboratory.—Position will require ability, training, and preferably experience in chemical engineering or chemistry, plus training or experience in technical filing. Work will involve planning and supervisory aspects and coordination of departmental filing systems and files. Give experience, education, and salary desired. Ethyl Corporation, 1600 W. 8 Mile Rd., Ferndale 20, Detroit, Michigan.

### CHEMICAL ENGINEER

Large Western New York synthetic organic chemical plant, noted for its high-quality manufacturing standards, has attractive permanent position for chemical engineer with 2 to 3 years' industrial experience on plant engineering projects. Liberal starting salary, with periodic review of performance for salary increases. Excellent working conditions, cafeteria, pension plan, plus group life, sickness and accident insurance. Reply in confidence to: Superintendent of Personnel Relations, Box 1-2.

Chemical Engineers—to do process research, must be graduate of recognized engineering college with some experience, married and 25 to 40 years old. Florida industry. Give full information with salary expected in first letter. Address all correspondence to P.O. Box 3269, Tampa 1, Florida.

Progressive well-established engineering company, specializing in large scale organic chemical work has opening for outstanding engineer. Prefer man of high scholastic rating and advanced training from an accredited school, plus some process design or project engineering experience. Employees notified of this advertisement. Box 2-2.

## SITUATIONS WANTED
### A.I.Ch.E. Members

Chemical Engineer—M.S. Columbia, 1949. Veteran, 24, single. Would like teaching position, but not interested in Ph.D. 1½ years' industrial experience; some teaching. Excellent scholastic record, Tau Beta Pi, Phi Lambda Upsilon, Sigmi Xi. Box 3-2.

Chemical Engineer—M.Ch.E., B.P.I. 5½ years' experience in process development, resins, coatings, chemical specialties, spray drying. Sigma Xi and Tau Beta Pi. Business administration background. Prefer northern New Jersey-New York area. Box 4-2.

Chemical Engineer—Desire to trade 3½ years of diversified experience in research and development, pilot plant design and operation, for challenging position with progressive company. Box 5-2.

Chemical Engineer—Ph.D. Nineteen years' teaching experience want summer employment (preferably industrial) or change in permanent employment. Available June 15 or on term's notice. Box 6-2.

Chemical Engineer—B.S.Ch.E., 26, single. Jr. Member A.I.Ch.E. and A.I.M.M.E. 3½ years in natural gas production, transmission and measurement. Desire responsible position with progressive oil or chemical company. Box 7-2.

Asphalt Specialist—Research, development, manufacturing. Over twenty years' specialized experience in paving, roofing, asphalts, road oils, additives. Seek responsible position in development or manufacturing. Box 8-2.

Lubricants—Long experience in manufacturing, research and development. Seek responsible position where technical skill and creative ability can be fully utilized—either refinery operations or industrial lubrication including additive syntheses. Box 9-2.

Chemical Engineer — Technical Sales — B.S.Ch.E., 28. Eight years' experience in process and sales engineering. Draft exempt. Desire to handle branch office for process equipment manufacturer. Box 10-2.

## SECRETARY'S REPORT

(*Continued from page 45*)

Council met Jan. 12, 1951, at The Chemists' Club. The minutes of the previous meeting were approved.

Dr. L. W. Bass who represents the Institute on the Committee on Unity in the Engineering Profession of Engineers Joint Council presented a prepared report of this committee which contained many recommendations as to possible plans for bringing about greater unity in matters of common interest to all engineers. Dr. Bass' report was accepted with thanks and it was voted that copies of the report be sent to all local sections by the president asking for their comments on the report at as early a date as possible.

G. F. Jenkins, L. B. Smith and D. J. Porter, who have constituted a subcommittee of the Public Relations Committee to study the question of whether a questionnaire should be sent to members of the Institute to obtain their opinions on several matters pertaining to Institute policies and practices, presented a complete report and also copy of a typical questionnaire which might be used. The Council did not act finally on this matter but will have it for business at a later meeting.

The appointment of representatives of the Institute with other groups for 1951 was completed and will appear in the Supplement to the 1950 Year Book.

The Council voted approval of the application for the authorization of the El Dorado Local Section of the Institute with headquarters at El Dorado, Ark. C. H. Davenport is chairman of this Section.

Stephen L. Tyler was appointed Executive Secretary for the year 1951.

## PEOPLE

### MURDOCK EXTENDS SERVICE TO MATHIESON

Mathieson Chemical Corp. recently announced that Harold R. Murdock, a staff member of Robert & Co. Associates, has been appointed a qualified and responsible engineer, through whom all of Mathieson's technical information is available to organizations interested in the application of sodium chlorite and chlorine dioxide to the bleaching of wood pulp, as well as the generation of chlorine dioxide from either sodium chlorate or sodium chlorite.

Dr. Murdock, known throughout the pulp and paper trade, for many years was director of research for the pulp divisions of The Champion Paper & Fiber Co. In 1946 he joined General MacArthur's staff in Japan, with the responsibility of rehabilitating the Japanese pulp and paper industry. He returned to the U. S. in the fall of 1949 and joined the Robert organization to supervise chemical process design, with special emphasis on pulp and paper.

**Herbert S. Isbin,** formerly chemical engineer, Hanford Works, General Electric Co., Richland, Wash., recently accepted an assistant professorship in chemical engineering at the University of Minnesota.

**Russ Wood** is associated as a chemical engineer with the engineering laboratory of Telechron, Inc., Ashland, Mass., a General Electric affiliate. In the past year he finished a 21-month training period with General Electric Co.

## Necrology

### S. L. HANDFORTH

Stanley L. Handforth, departmental engineer of the explosives department of the Du Pont Co., died suddenly Jan. 7. He was 54 years old. Early in his career he was associated with W. S. Fleischer & Co., Engineers, New York, and with Henry P. Adams & Co., Engineers, San Francisco, Calif. He joined Du Pont in 1927 as a chemical engineer in the Eastern Laboratory, Gibbstown, N. J., working on chemical engineering research and development, later transferred to the engineering department in Wilmington, assigned to development and process design work. Subsequently he became design project manager and departmental engineer, explosives department, in 1947. During his career with Du Pont a number of patents were issued on his inventions in connection with nitric acid and ammonium nitrate.